Searches for Long Lived Particles at the LHC – and Beyond

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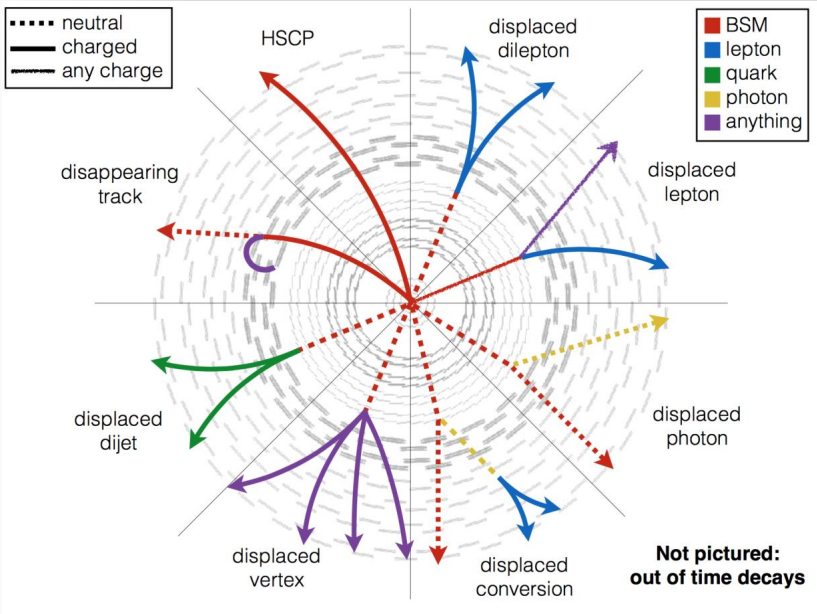
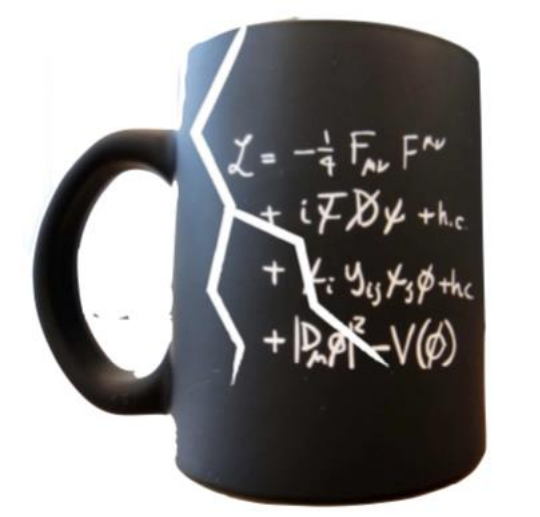
7 December FNAL

Physics Opportunities in the Near DUNE Detector hall: PONDD

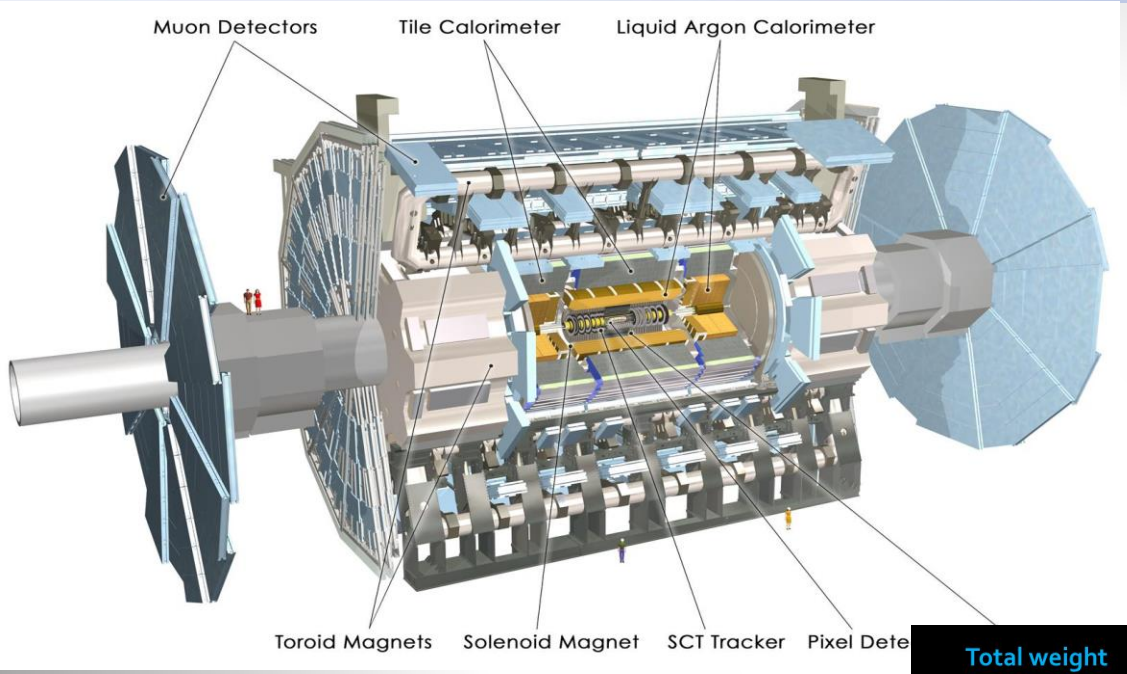




Outline

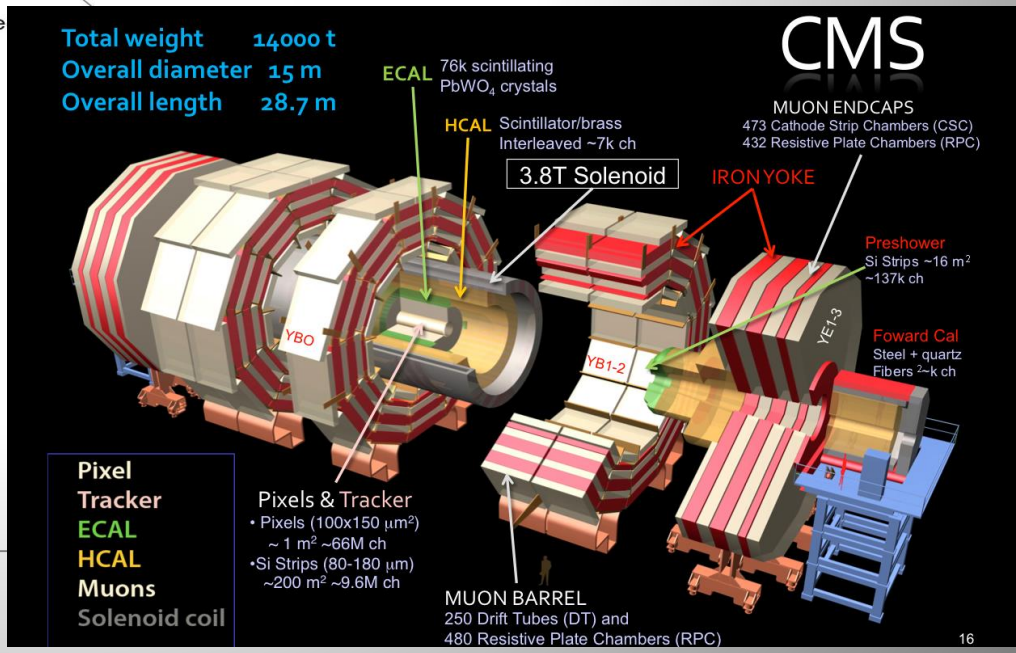
- Introduction to long lived exotic particles: why do we care?
- Challenges at the LHC
- New experiments for the LHC?
- Other opportunities for LLPs searches
- Summary/Outlook

New Physics Hunters @ the LHC

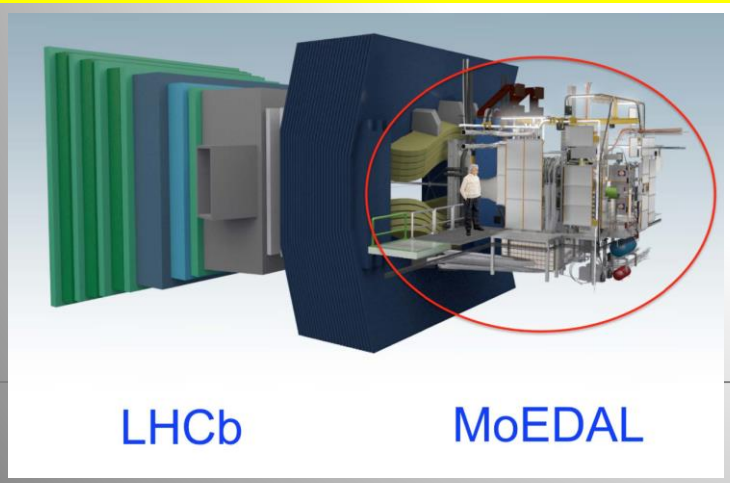


The ATLAS experiment

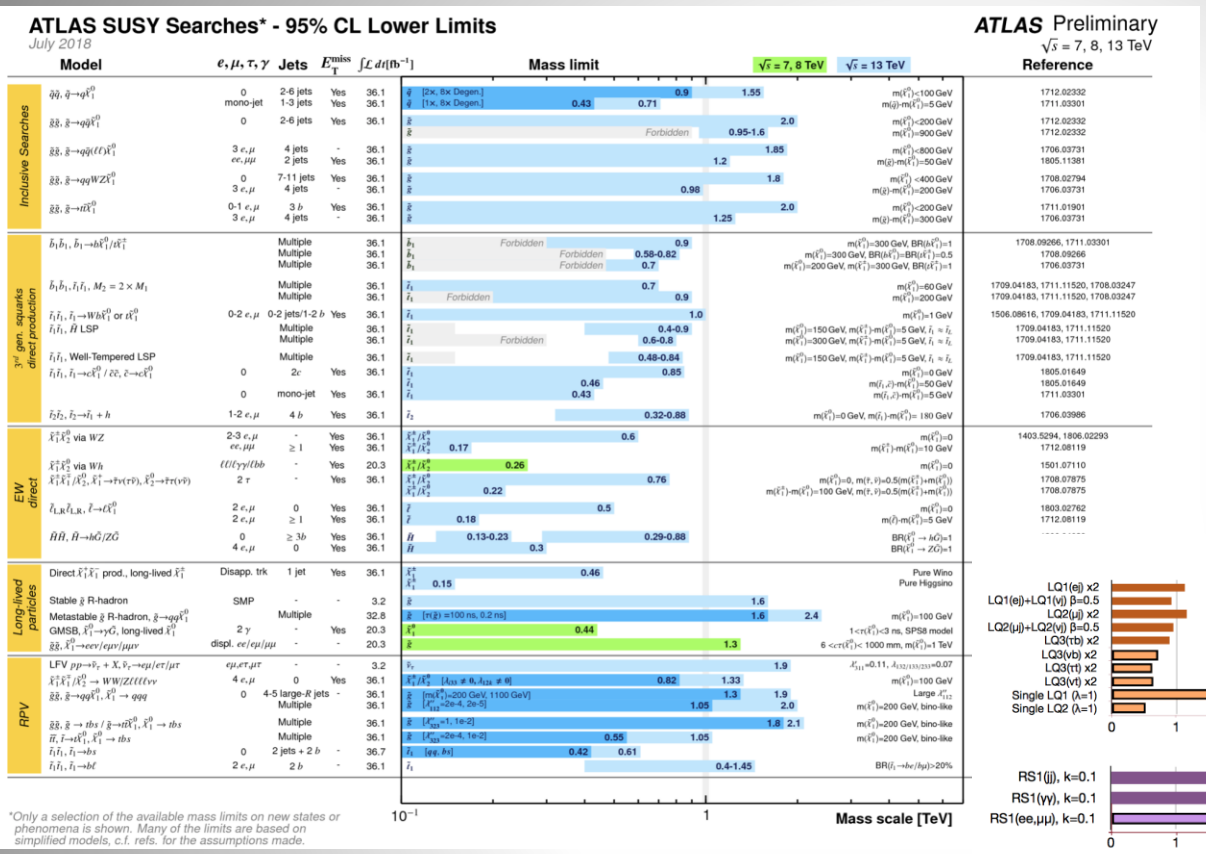
The CMS experiment



...And also LHCb and MoEDAL

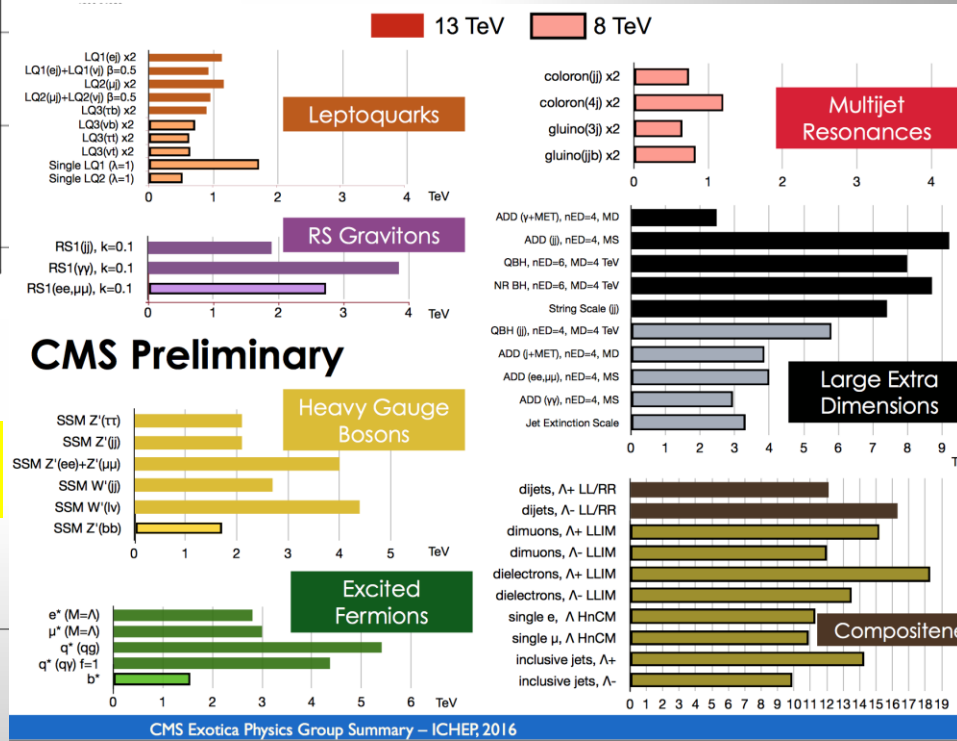


LHC: So far no new physics



Classical Searches
-Superymmetry
-Exotica
-Flavor Universality
-...

No signal of new physics so far!!



Are we leaving no stone unturned?

- The LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics (higher mass, lower couplings)
- But if we still do not see more than a 2 sigma at the end of run 3, the HL-LHC will be likely mostly a precision physics machine, searching for subtle deviations
- Are we looking at the right place? Time for more effort in thinking of complementary searches?

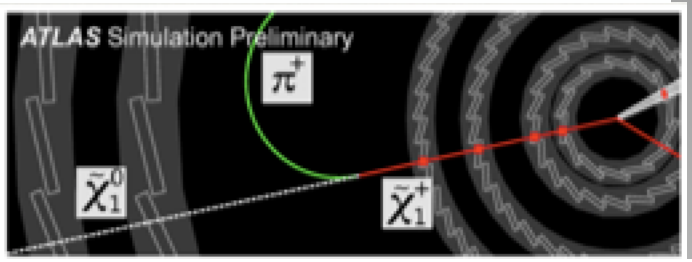
Are we looking at the right place?

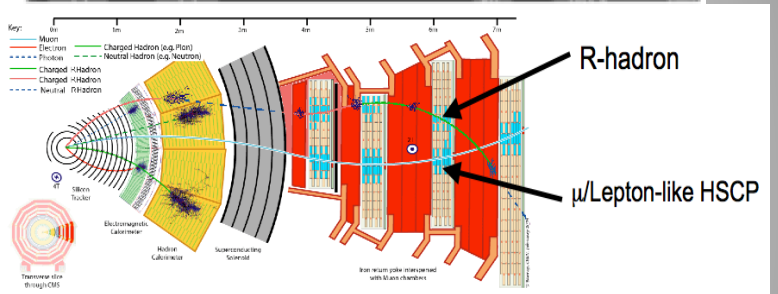
Leave no stone unturned!!

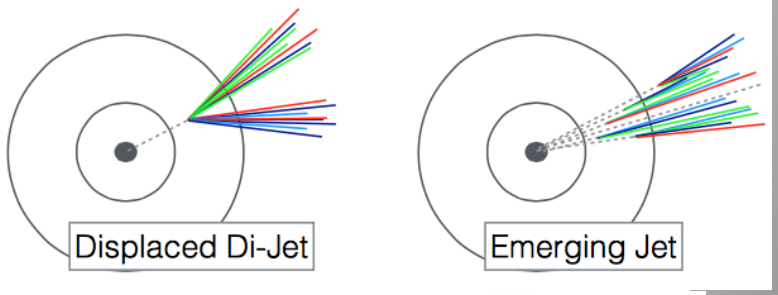
Long Lived Particles

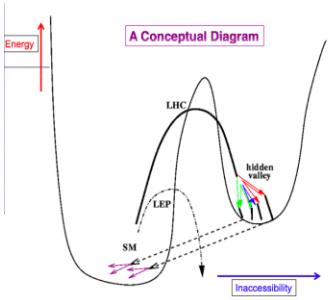
Long lifetimes arise from a hierarchy of scales or a small coupling

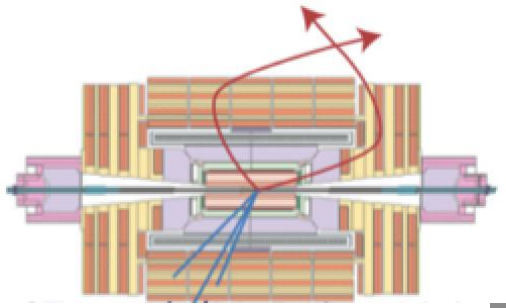
- RP Violating SUSY
- ASMB SUSY
- Gauge Mediated SUSY
- Split SUSY
- Hidden Valleys Models
- Dark QED/Dark Photons
- Monopoles
- Quirk Models
- Dark Matter Models…
- Stable Sexaquarks
- Axion-Like Particles
- ….





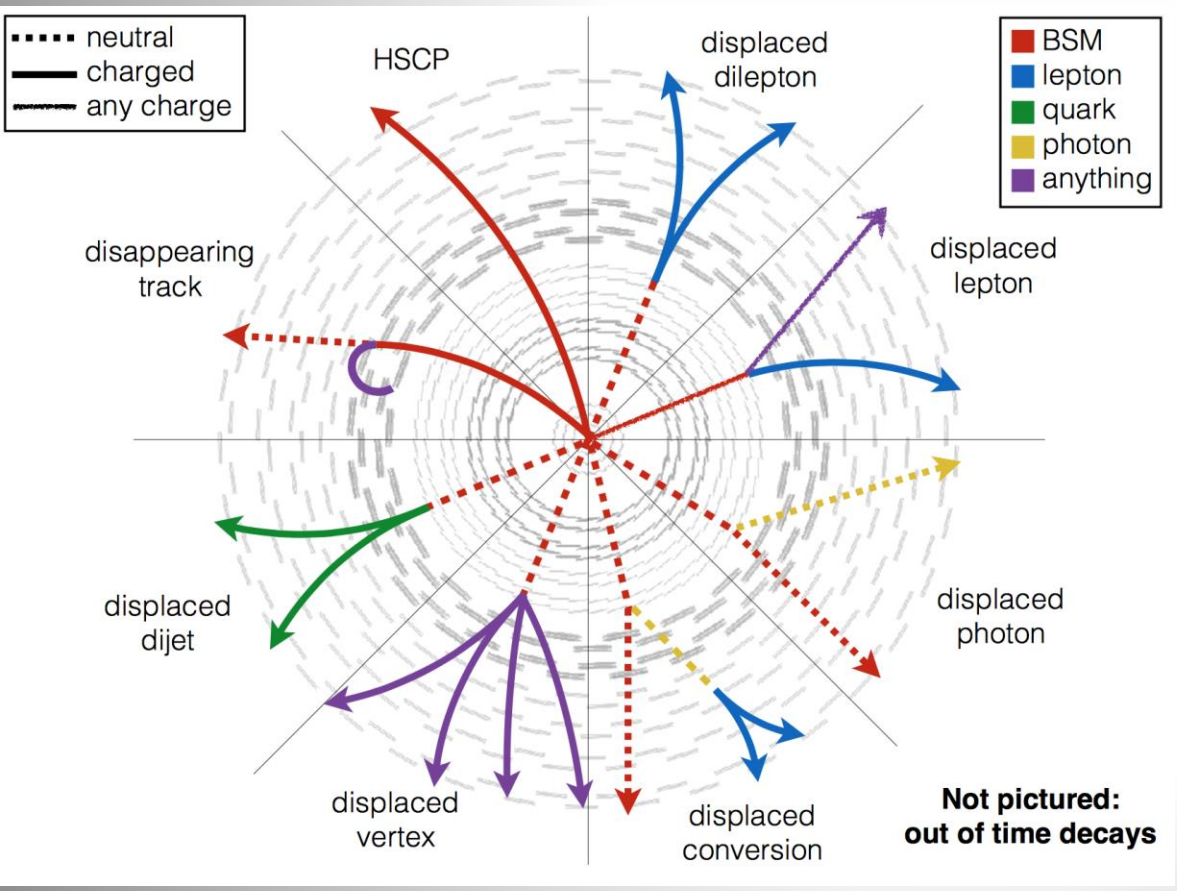






Long Lived Particles @LHC

Signatures



Some of the Challenges

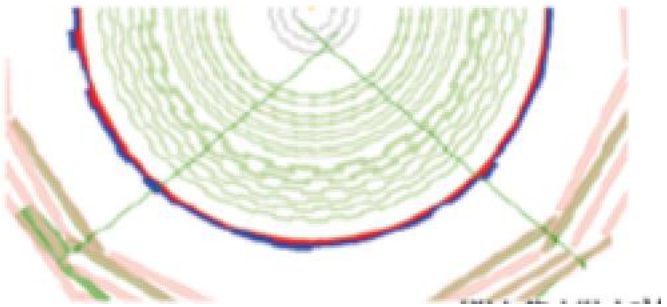
Triggers: Tracking detectors are powerful but difficult to use in trigger

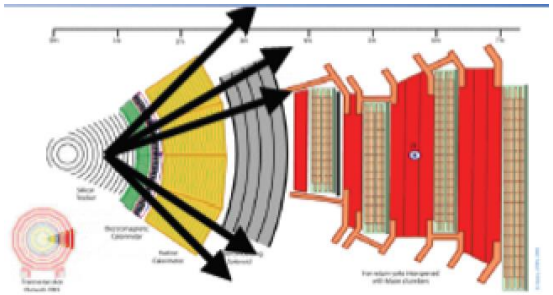
Backgrounds often low. But need special studies (punch through, secondary interactions, cosmics…)

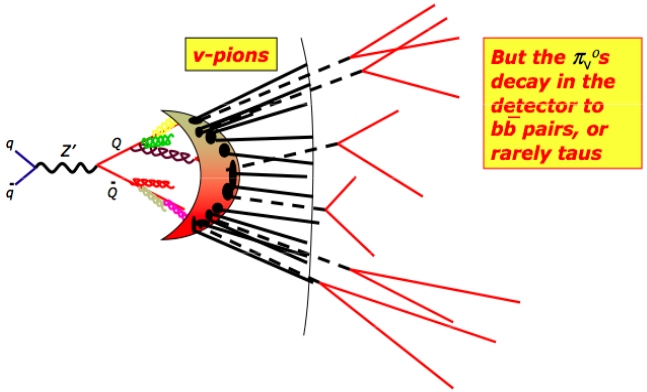
Special reconstruction is often needed

Long Lived Searches Overview

- Displaced jets, dijets, vertices
- Disappearing tracks
- Displaced leptons & lepton jets
- Displaced photons
- Dark photon decays
- Heavy Stable Charged Particles
- Stopped particles
- Emerging jets
- Monopoles stuck in material
- Heavy Neutral Lepton searches
- Strongly Interaction Massive Particles
- …. (others…new ideas…)

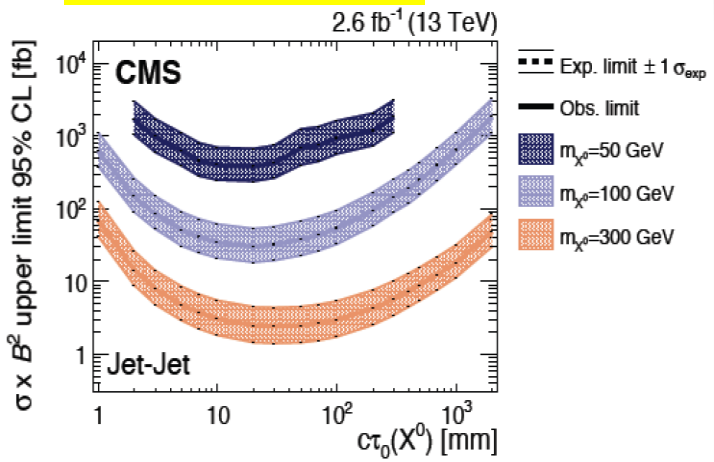




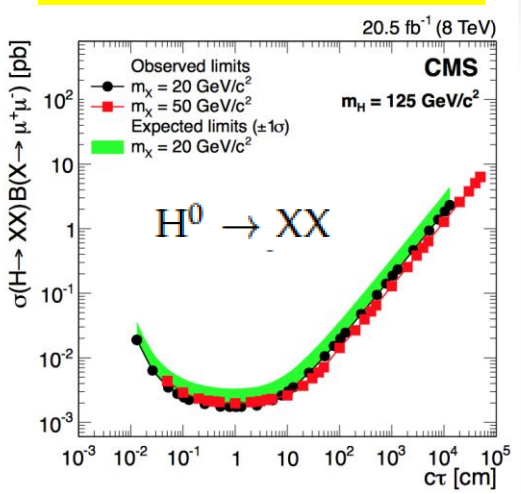


Long Lived Searches: Examples

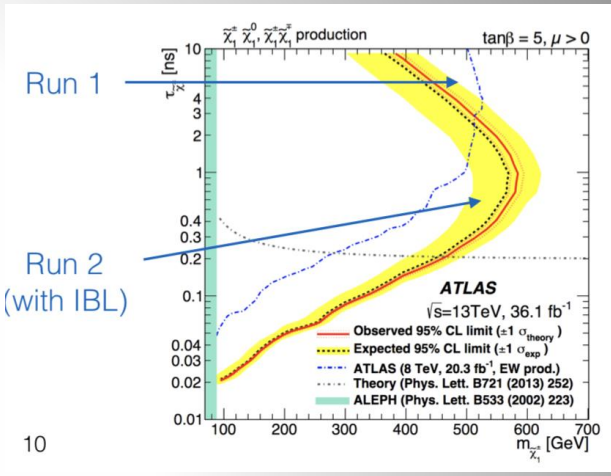
displaced jets



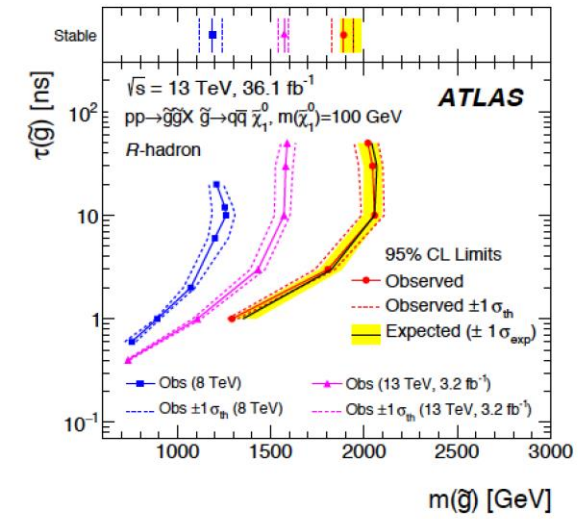
displaced leptons



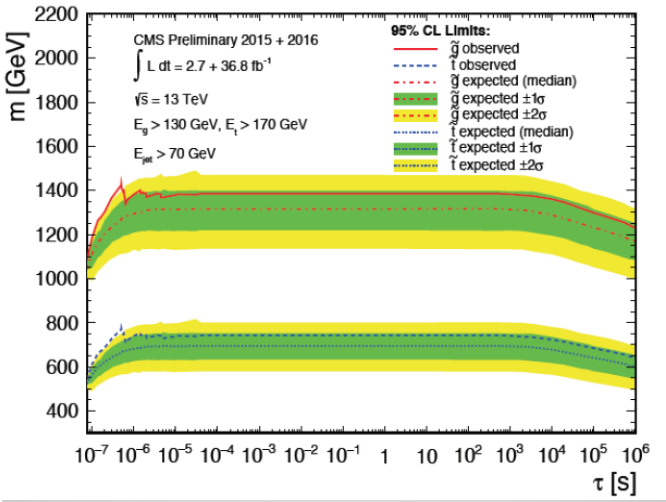
disappearing tracks



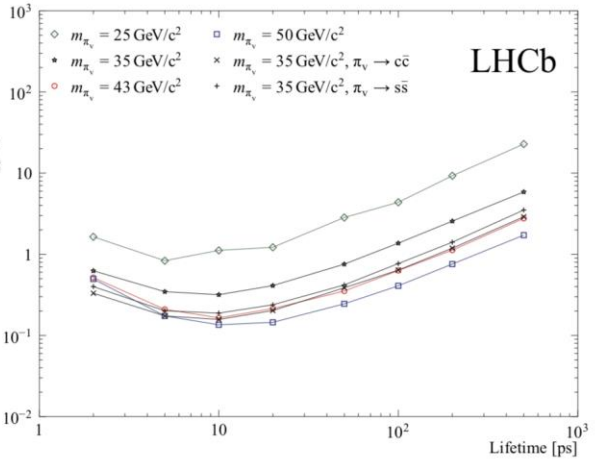
metastable R-hadrons



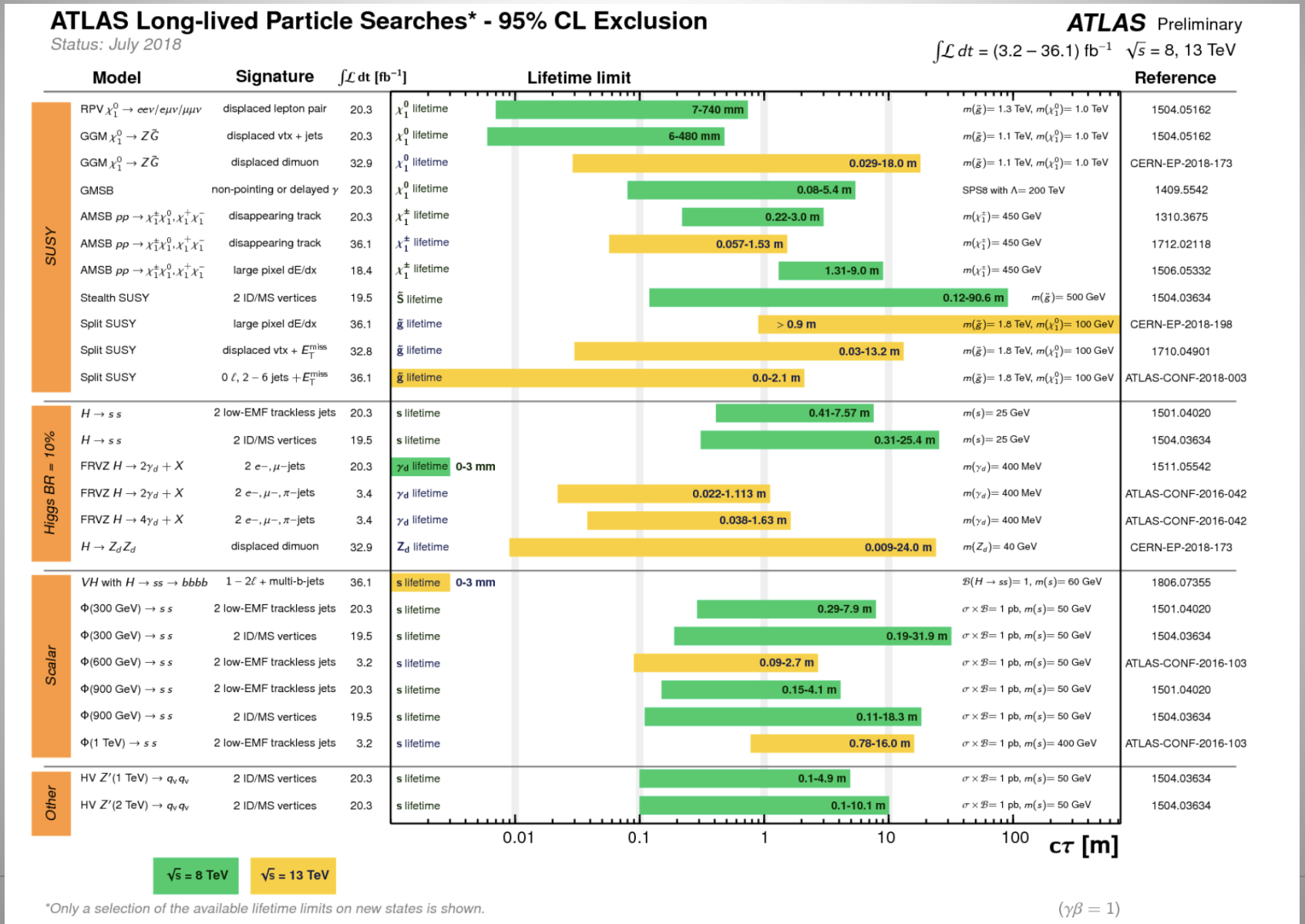
stopped particles



Hidden Valley searches



Long Lived Particle Searches

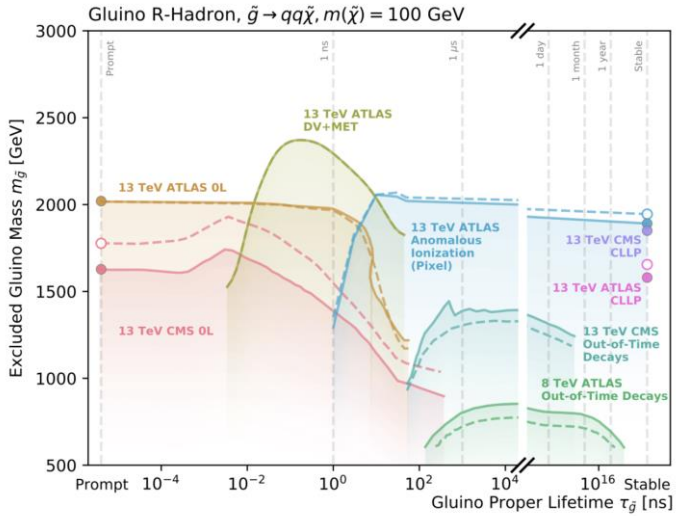


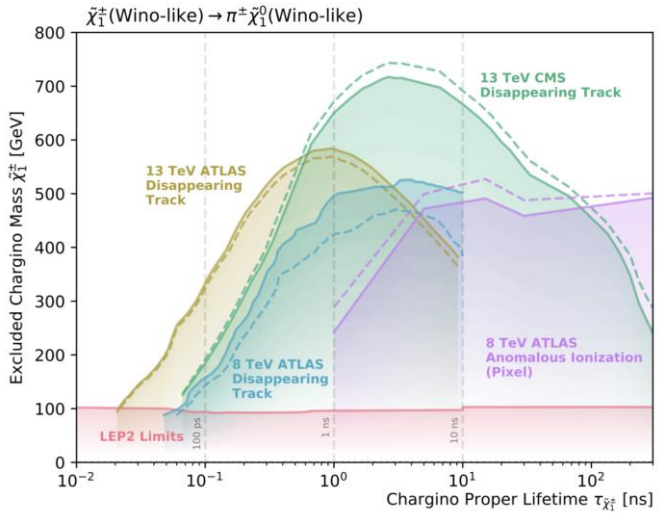
Long Lived Particle Searches

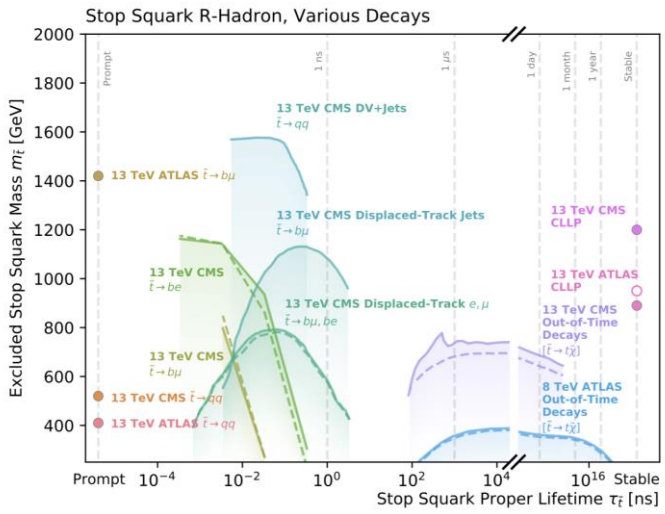
arXiv:1810.12602

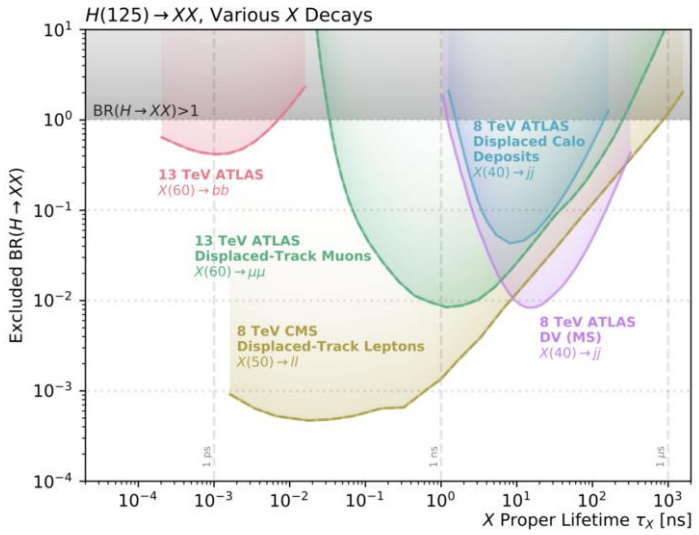
Collider Searches for Long-Lived Particles Beyond the Standard Model

Lawrence Lee[1], Christian Ohm[2,3], Abner Soffer[4], Tien-Tien Yu[5,6]





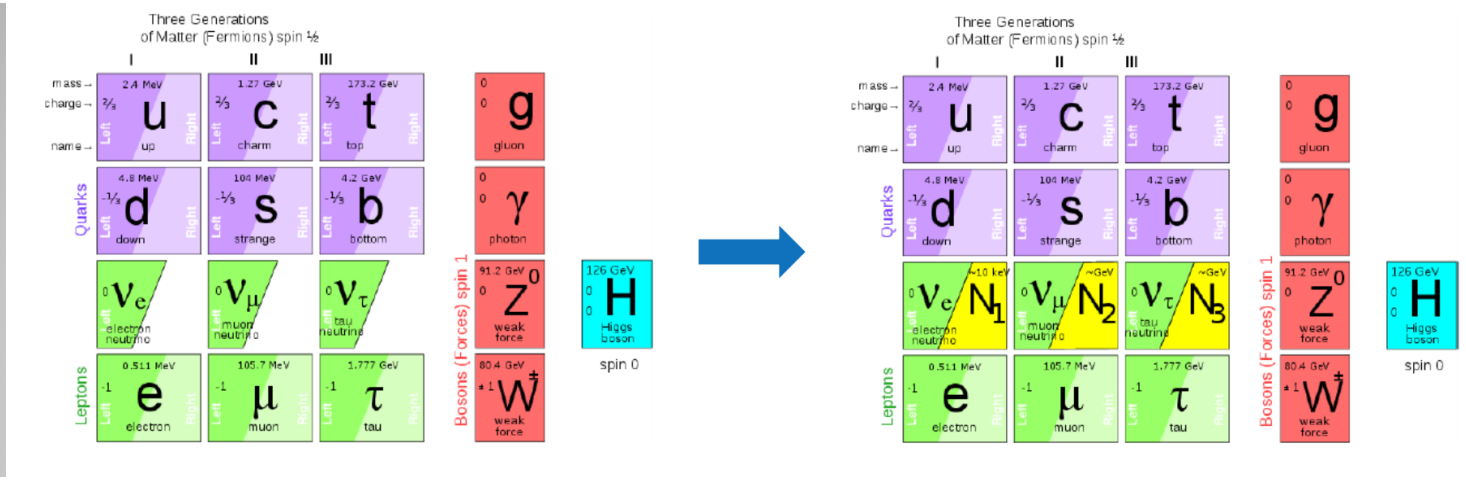


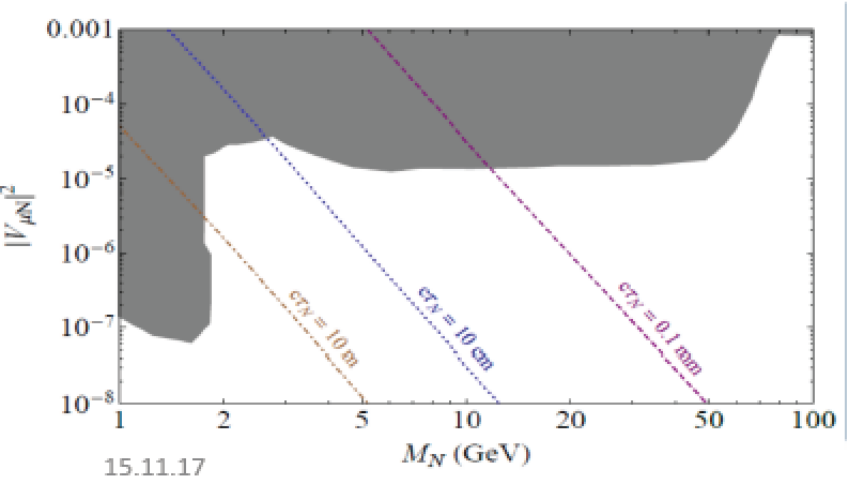


Summary plots from the above reference, on the present coverage

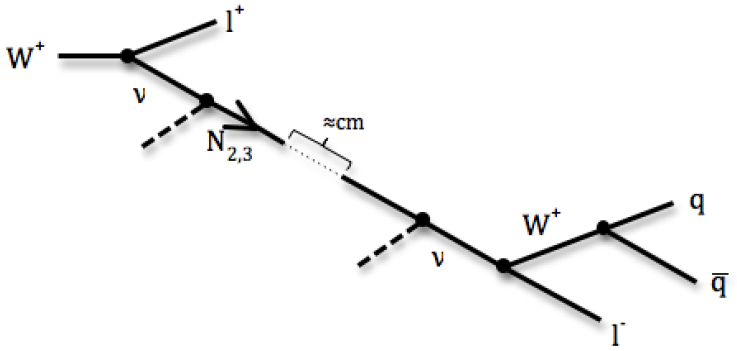
Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.





D.Gorbunov, M.Shaposhnikov JHEP 0710 (2007) 015

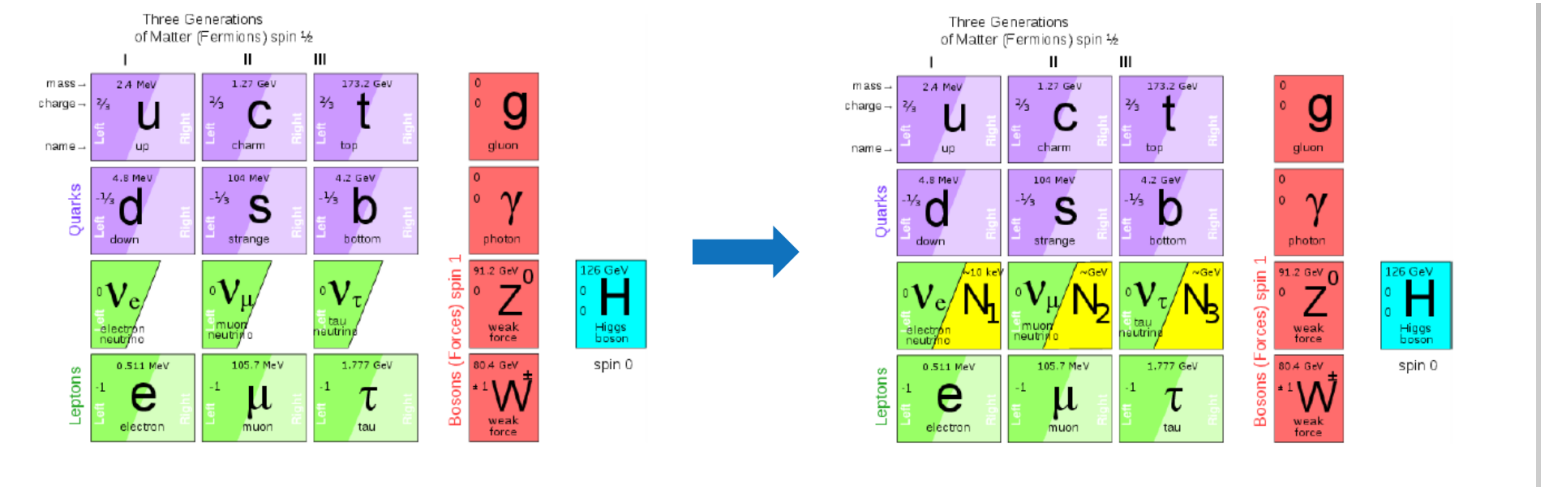


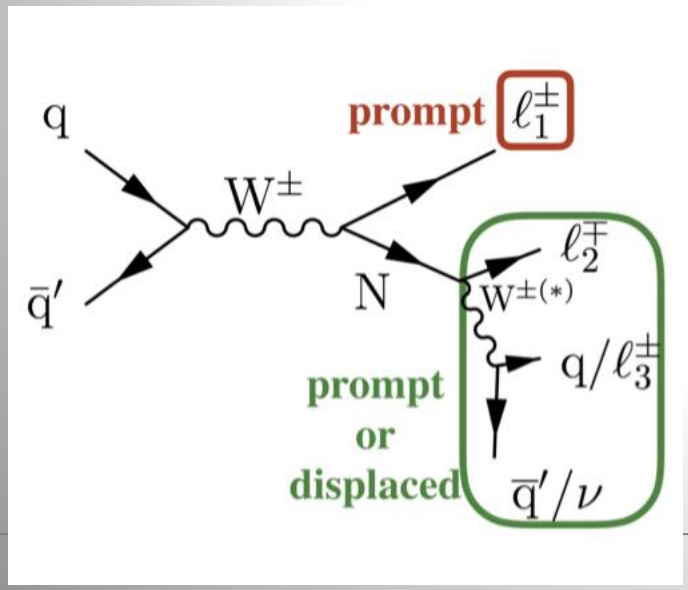
First LHC results on prompt studies
Majorana/Dirac? Now studies with displaced jets/lepton analyses. L~ 1m?

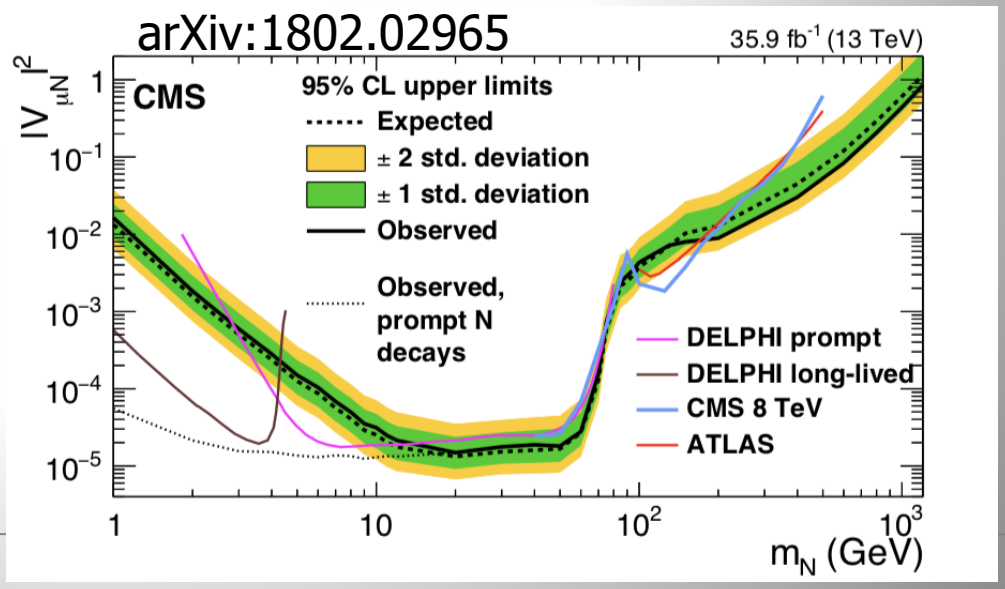
Search for Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)

Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.



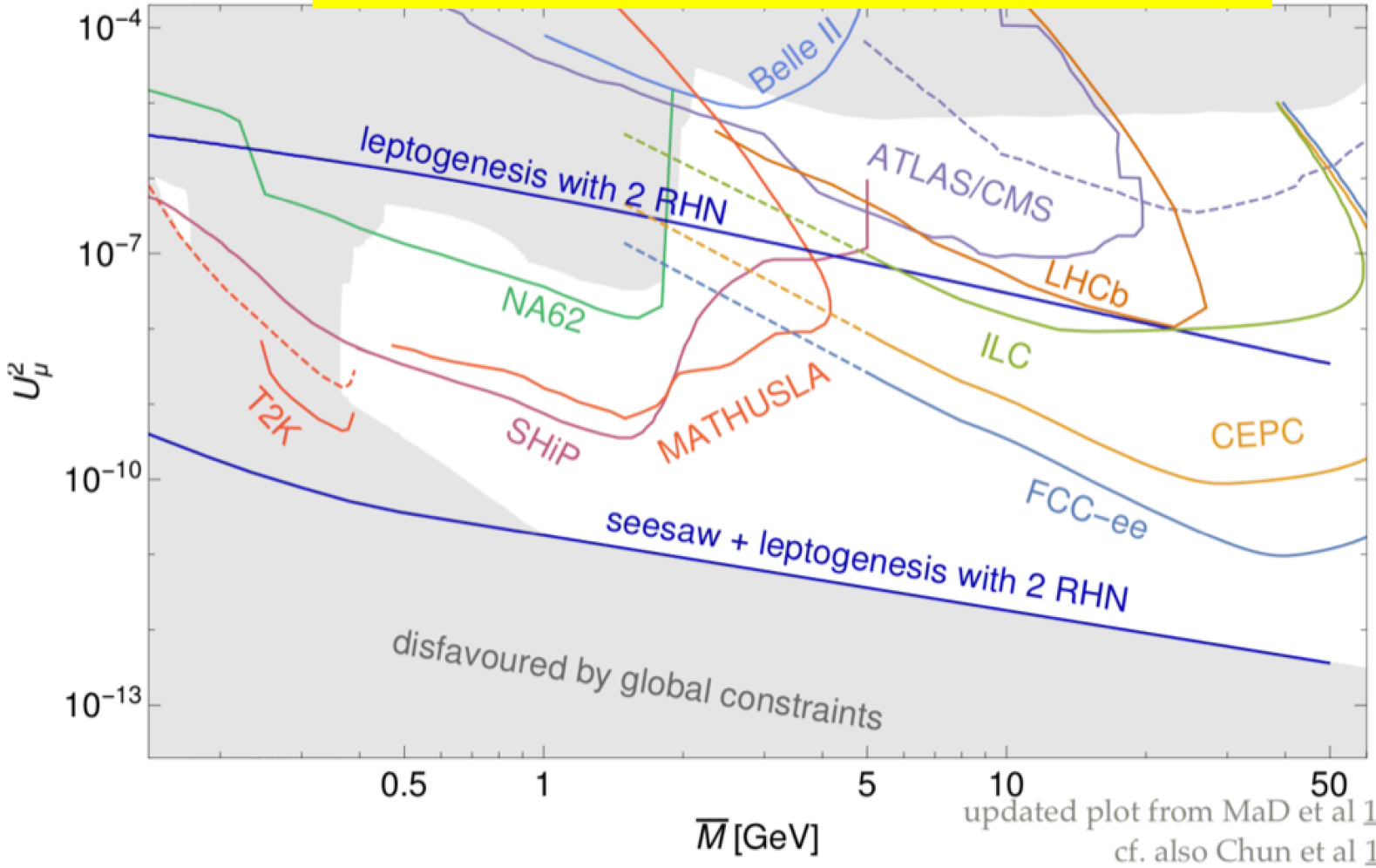




Search for Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.

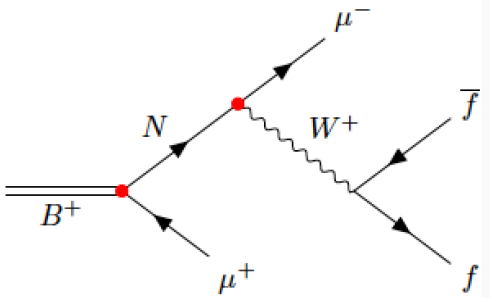
Sensitivity plot for HNLs/Marco Drewes et al.



updated plot from MaD et al 1609.09069
cf. also Chun et al 1711.02865
Cai et al 1711.02180

BSM Searches in Heavy Ions

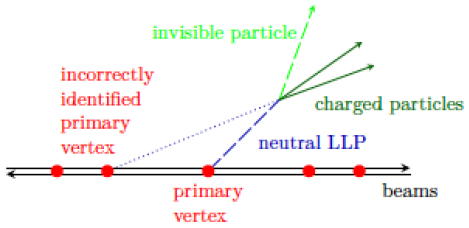
arXiv:1810.09400



Advantage

- no pile-up; single primary vertex
- large nucleon multiplicity
  e.g. $A(\mathrm{Pb}) = 208$, $Z(\mathrm{Pb}) = 82$
- Number of parton level interactions per collision scales with A
  e.g. $\frac{\sigma_{\mathrm{PbPb}}}{\sigma_{pp}} \propto A^2 = 43\,264$

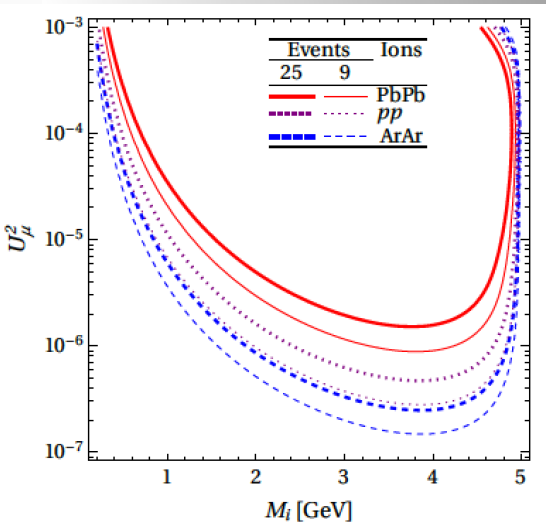
Single primary vertex



Better event reconstruction possible

Drawbacks

- There are a huge number of tracks near the interaction point which makes the search for prompt new physics extremely challenging
- The collision energy per nucleon is smaller. e.g. $\sqrt{s_{NN}} = 5.02\,TeV$ for Pb which is problematic for heavy new physics
- The instantaneous luminosity is lower for larger A
- The LHC has allocated much less time to heavy ions runs than to protons runs
- The experiments might not wish to collect the maximal possible luminosity
  e.g. LHCb uses about 10 % of the available luminosity for its QGP studies



Reach for equal run times, including the luminosity limitations

Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac '31)

$$\nabla.\mathbf{E} = 4\pi\rho_e$$

$$\nabla.\mathbf{B} = 4\pi\rho_m$$

$$-\nabla\times\mathbf{E} = \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j_m}$$

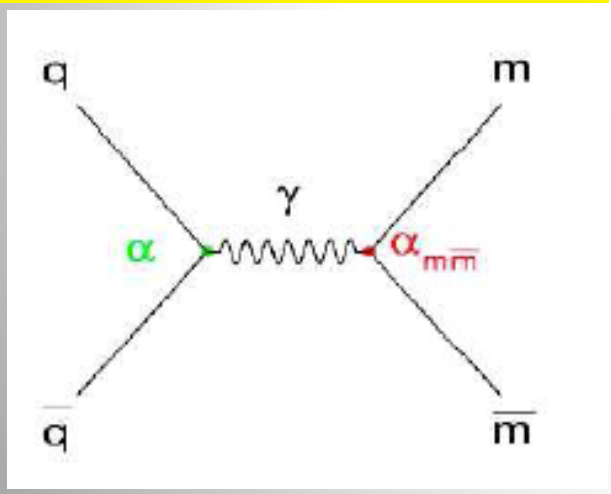
$$\nabla\times\mathbf{B} = \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$

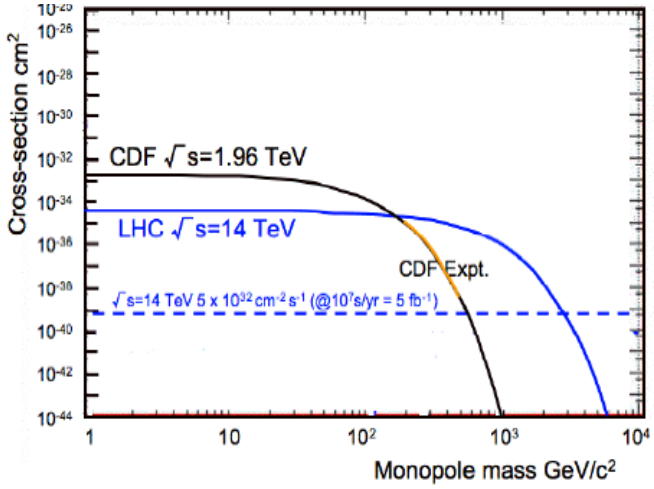
$$\mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right) + q_m\left(\mathbf{B} - \frac{\mathbf{v}}{c}\times\mathbf{E}\right)$$

$$eg = n\hbar c/2 = n g_D$$ = n 68.5e

$$\sigma_{D(m)} = \left(\frac{g_D}{e}\right)^2 \times \sigma_{\mu\mu}(>2m) \times (1 - 4\frac{m^2}{s})$$

Symmetrizes Maxwell equations
Searched for at all colliders
Tevatron direct limits ~ 400-800 GeV





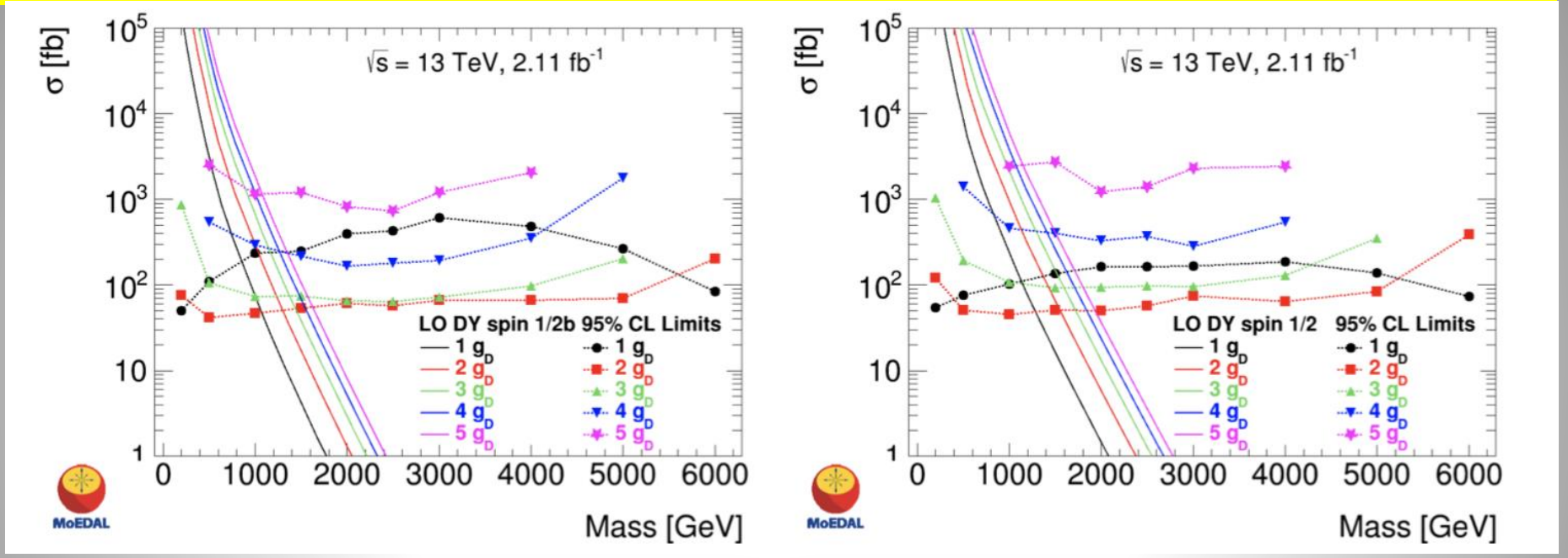
Sensitivity of LHC experiments to exotic highly ionising particles

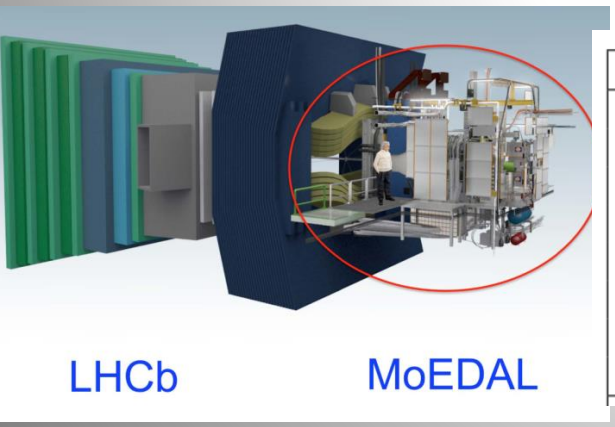
A. De Roeck[1,2,3], A. Katre[4], P. Mermod[a,4,5], D. Milstead[6], T. Sloan[7]

arXiv: 1112.2999

Monopole Searches: MoEDAL @ 13TeV

2016 data analysis base on 222 kg Aluminium to "stop" the monopoles and search for them with a SQUID precision magnet (2.11fb^{-1}) arXiv:1712.09849

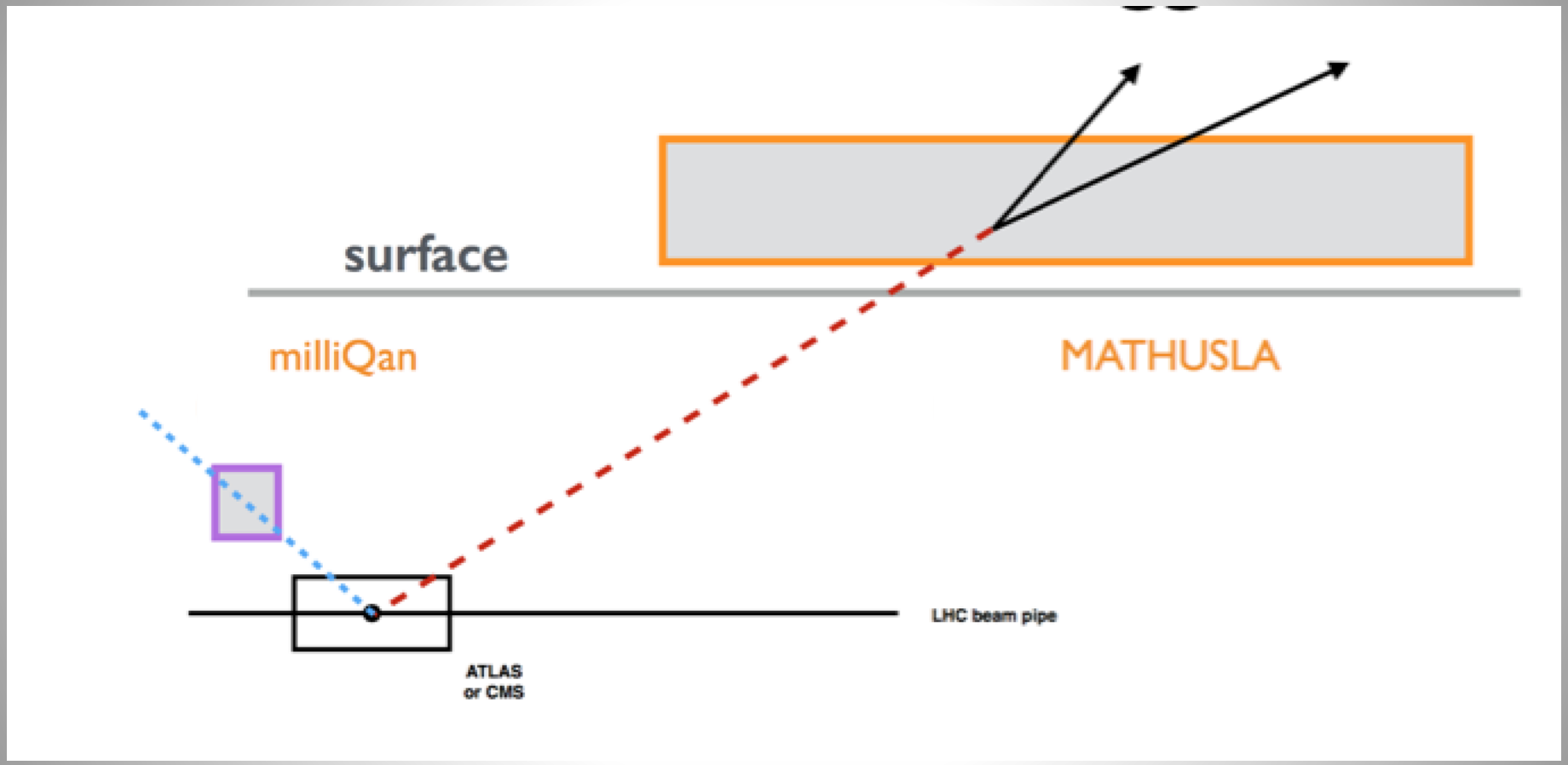




Mass limits [GeV]	$1g_D$	$2g_D$	$3g_D$	$4g_D$	$5g_D$
MoEDAL 13 TeV (2016 exposure)					
DY spin-0	600	1000	1080	950	690
DY spin-$\frac{1}{2}$	1110	1540	1600	1400	–
DY spin-1	1110	1640	1790	1710	1570
DY spin-0 β-dep.	490	880	960	890	690
DY spin-$\frac{1}{2}$ β-dep.	850	1300	1380	1250	1070
DY spin-1 β-dep.	930	1450	1620	1600	1460

- Limits for different monopole charges
- First monopole search result @LHC at 13 TeV No signal yet..

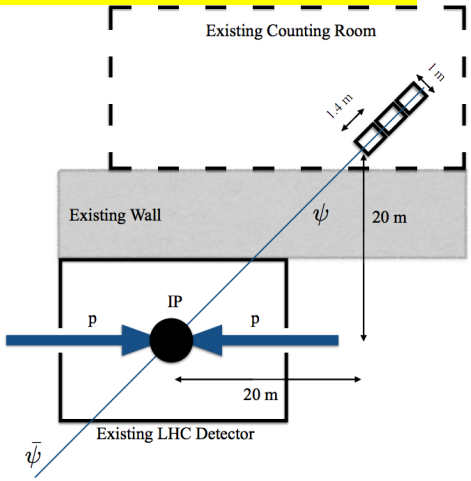
New Detector Ideas



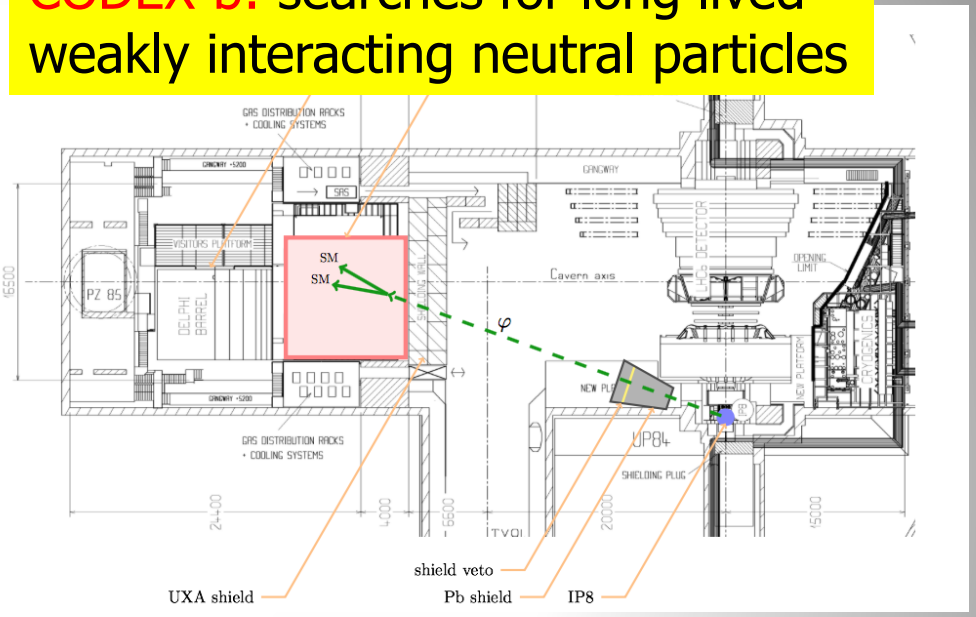
Prototyping ongoing/demonstrators in place
Aim for the LHC run starting 2026 (phase 2)

Proposals for New Experiments @LHC

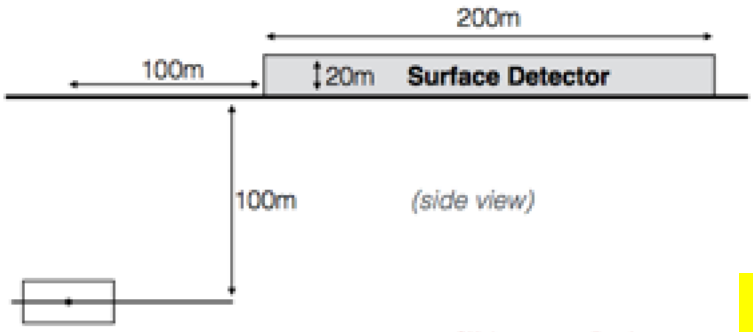
MilliQan: searches for millicharged particles



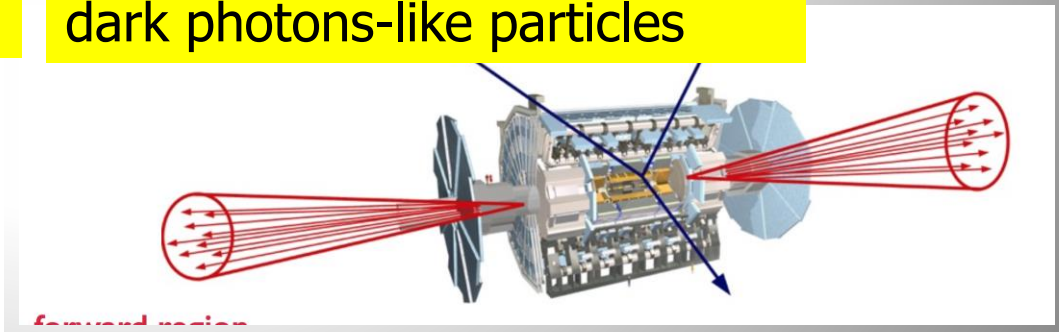
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles



FASER: searches for long lived dark photons-like particles



New: AL3X ('ALICE' for LLP arXiv.1810.03636)...

Particles with Milli-Charges?

"New" idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector ->

A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

arXiv:1607.04669

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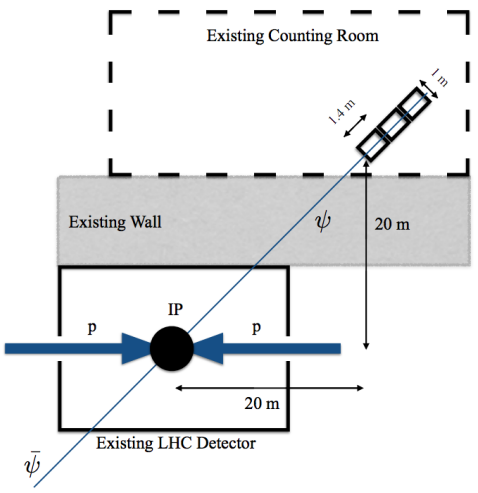
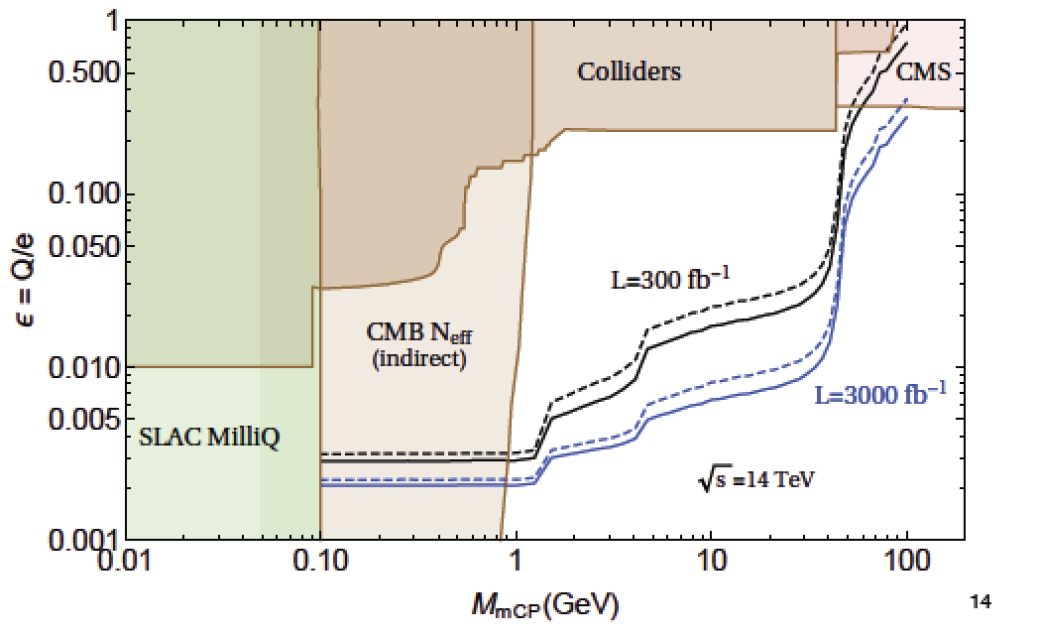
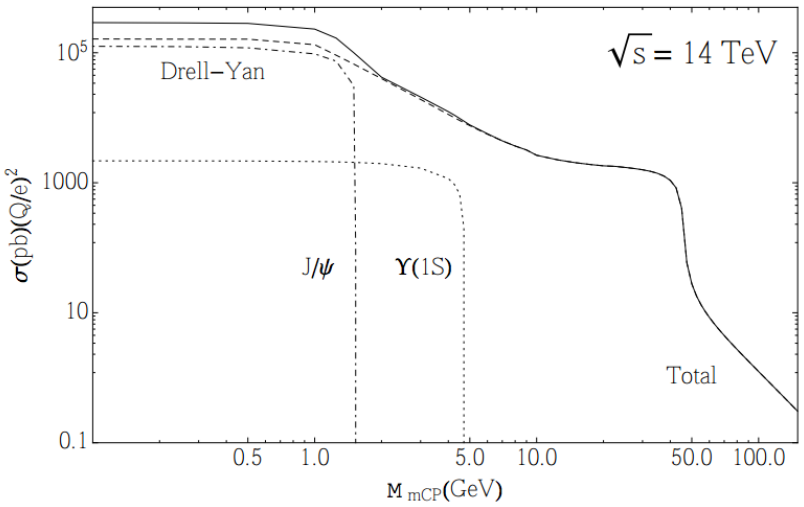


MilliQan Experiment



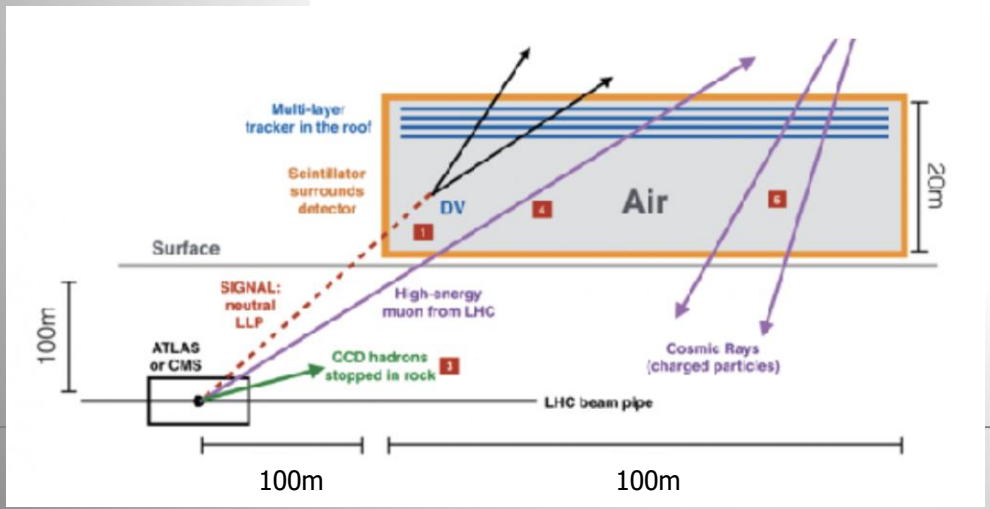


MATHUSLA

A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

CERN-LHCC-2018-25



A proposal for a large area surface array to detect ultra long lived particles coming from the pp collisions

Aim to cover the range

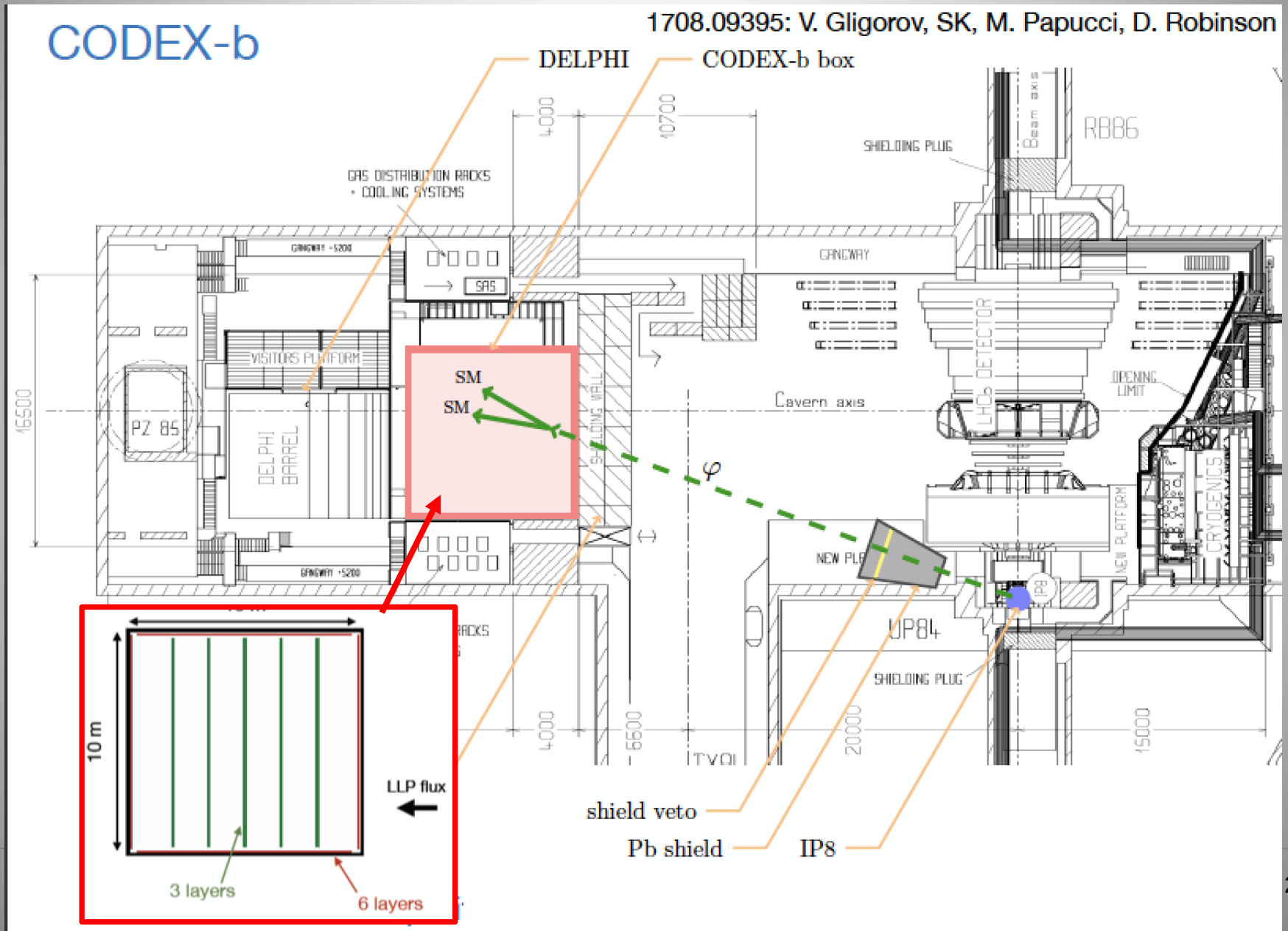
$$c\tau \lesssim 10^7 - 10^8 \text{ m}$$

~ BBN constrained inspired

Physic case arXiv:1806.07396

Possible detector surface array eg above ATLAS or CMS: ~ $(100\text{m})^2$

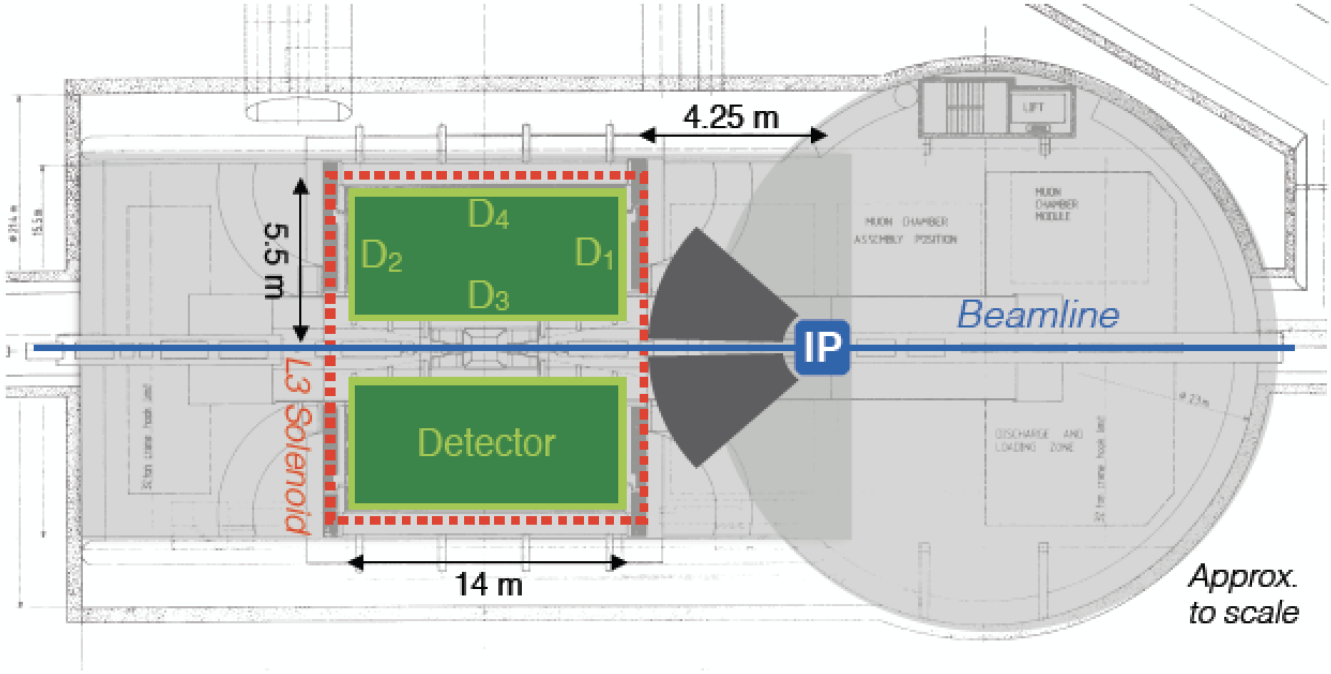
CODEX-b Proposal



Re-using ALICE (Run 5)?

A Laboratory for Long-Lived eXotics (AL3X)

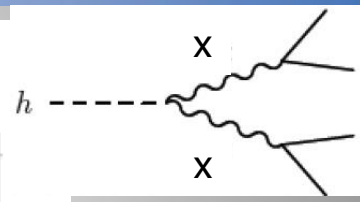
Reuse the L3 magnet and (perhaps) the ALICE TPC

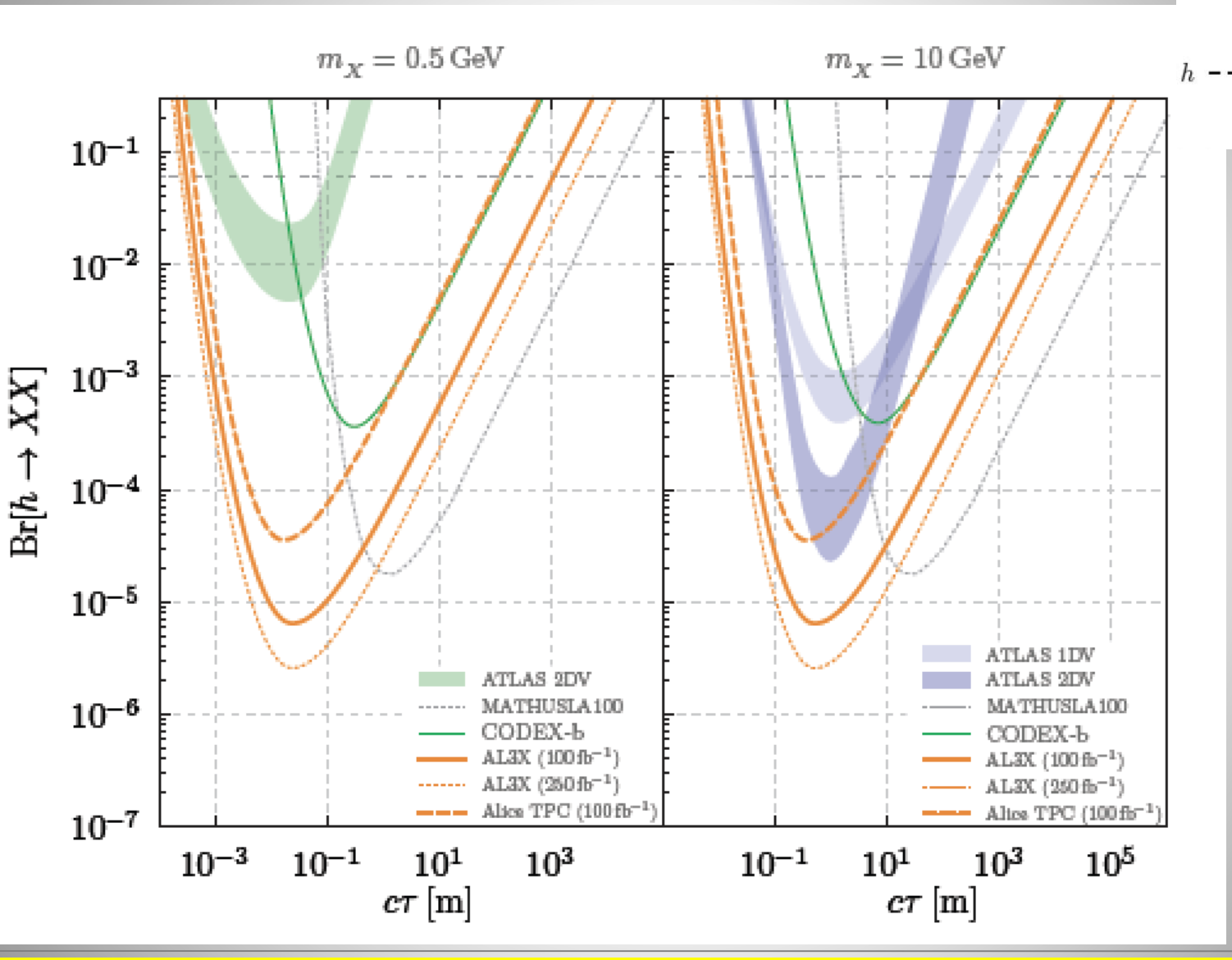


Similar strategy as for CODEX-b: use thick shield with active veto to reduce the backgrounds

V. Gligorov, SK, B. Nachman, M. Papucci, D. Robinson: 1810.03636

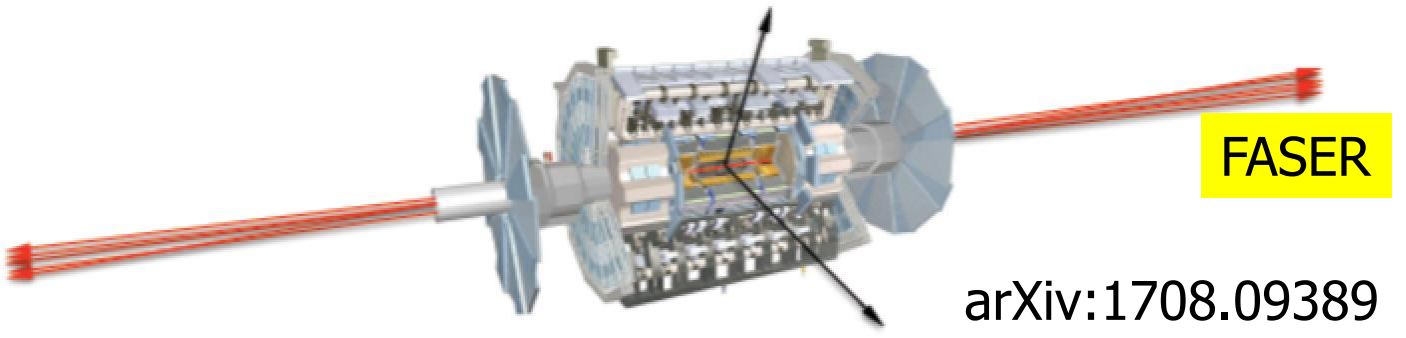
Physics Reach: Example

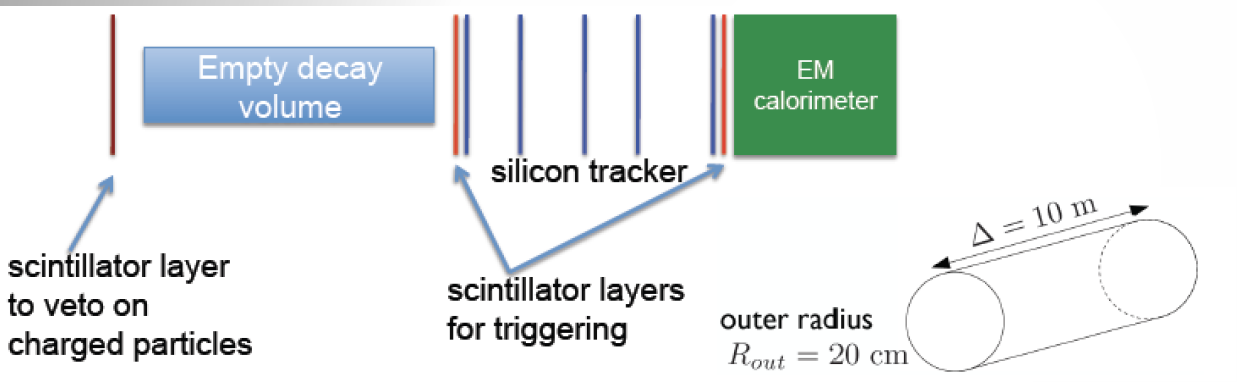


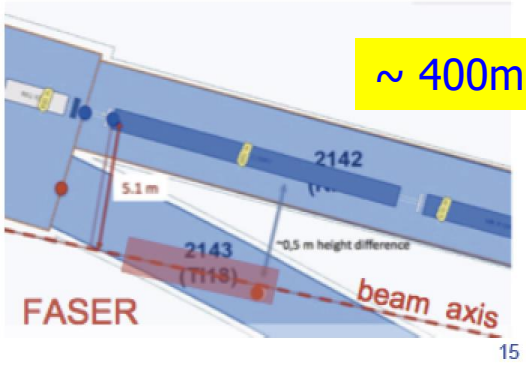


For low masses: MATHUSLA, CODEX-b and AL3X have a leading edge

FASER Proposal







- FASER has significant discovery potential for dark photons dark Higgs bosons, heavy neutral leptons (sterile neutrinos), ALPs, other gauge bosons, and many other new particles.

- Currently have in mind an initial veto layer, followed by ~5 tracking layers and EM calorimeter, with volume largely empty and a magnetic field.

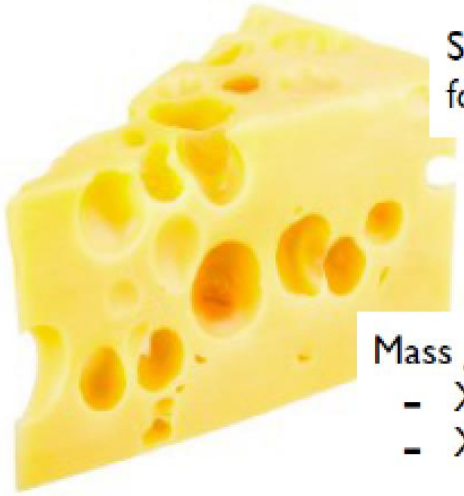
Current Neutral LLP Searches

2016

Exp	Search	run	signal	LLP Daughters	LLP Scale	Parent Scale	Associated Objects	# LLP Decays	decay Location	decay Detector	L1 trigger
CMS	EXO-12-035-pas	8 TeV	GMSB neutralino → γ + G	γ + MET	100-300 GeV	x2 + ~ 50	jets, MET	1	tracker	ECAL (timing)	one photon
	EXO-14-017-pas	8 TeV	GMSB neutralino → γ + G	γ + MET	200-300 GeV	x2 + ~ 50	MET	2	tracker	tracker (convers	diphoton
	1211.2472	7 TeV	H->XX	2 leptons	20+ GeV	100+ GeV	none	2	tracker	same	dilepton
	1411.6530v2	8 TeV	H->XX, RPV SUSY	2 jets	50+ GeV	200+ GeV	none or jets	1	tracker	same	HT > 300 GeV
	1411.6977	8 TeV	H->XX, RPV SUSY	2 leptons	20+ GeV	100+ GeV	none	1	tracker	same	dilepton
	1409.4789	8 TeV	RPV SUSY	e and mu	0.5 – 1 TeV	x2	none	2	tracker	tracker, MS	one muon
ATLAS	1504.03634	8 TeV	H->XX, HV Z', Stealth SUSY	2x ~ anything	10+ GeV	100+ GeV	none	2	Muon System	same	Muon RoI
	1501.04020	8 TeV	H->XX	2x ~ anything	10+ GeV	100+ GeV	none	2	HCAL	same	CalRatio
	1409.0746	8 TeV	H → HV .. → X X	2 leptons	0.4 – 2 GeV	~ 100 GeV	none	2	tracker	same	standard lepton(s)
	1504.05162	8 TeV	SUSY (split, rpv, gmsb)	2 leptons or 5+ charges	10+ GeV	600+ GeV	various		tracker	same	HARD MET, Jet, lepton
LHCb	1412.3021	7tev 0.62/fb	H->XX	2 quarks	25 – 50 GeV	100 GeV	none	1	0.4-4.8mm From beam	tracker	single track > 1.5 – 3.5 GeV

Need a more systematic approach

not yet

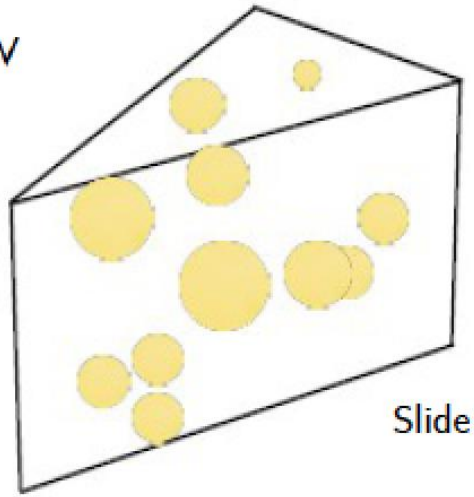


Shorter lifetimes: identify DV for < ~ mm displacements

Mass gaps in current searches:

- X→ leptons: 2 - 20 GeV
- X→ hadrons: < 10 GeV

more like



Slide from D. Curtin

LHC White Paper in Preparation

Web page: https://indico.cern.ch/event/649760

Searches for long-lived particles at the LHC: Second workshop of the LHC LLP Community

17 Oct 2017, 16:00 → 20 Oct 2017, 18:00 Europe/Zurich

Giambiagi Lecture Hall (ICTP, Trieste, Italy)

Albert De Roeck (CERN) , Bobby Samir Acharya (Abdus Salam Int. Cent. Theor. Phys. (IT)) , Brian Shuve (SLAC National Accelerator Laboratory) , James Beacham (Ohio State University (US)) , Xabier Cid Vidal (Universidade de Santiago de Compostela)

Next workshop: 27-29 May 2019 CERN

White paper — chapter statuses and roundtable
[draft here (18 Oct)]

- Simplifed models — First draft done!
- Experimental coverage — First draft essentially done!
- Triggers, upgrades, HL- / HE-LHC opportunities
  — First draft in progress
  —> discussion today [live doc!]
- Re-interpretations / recommendations
  — First draft imminent!
- Backgrounds — First draft imminent!
- Dark showers
  — First draft (summarizing status and advertising for

White Paper being finalized

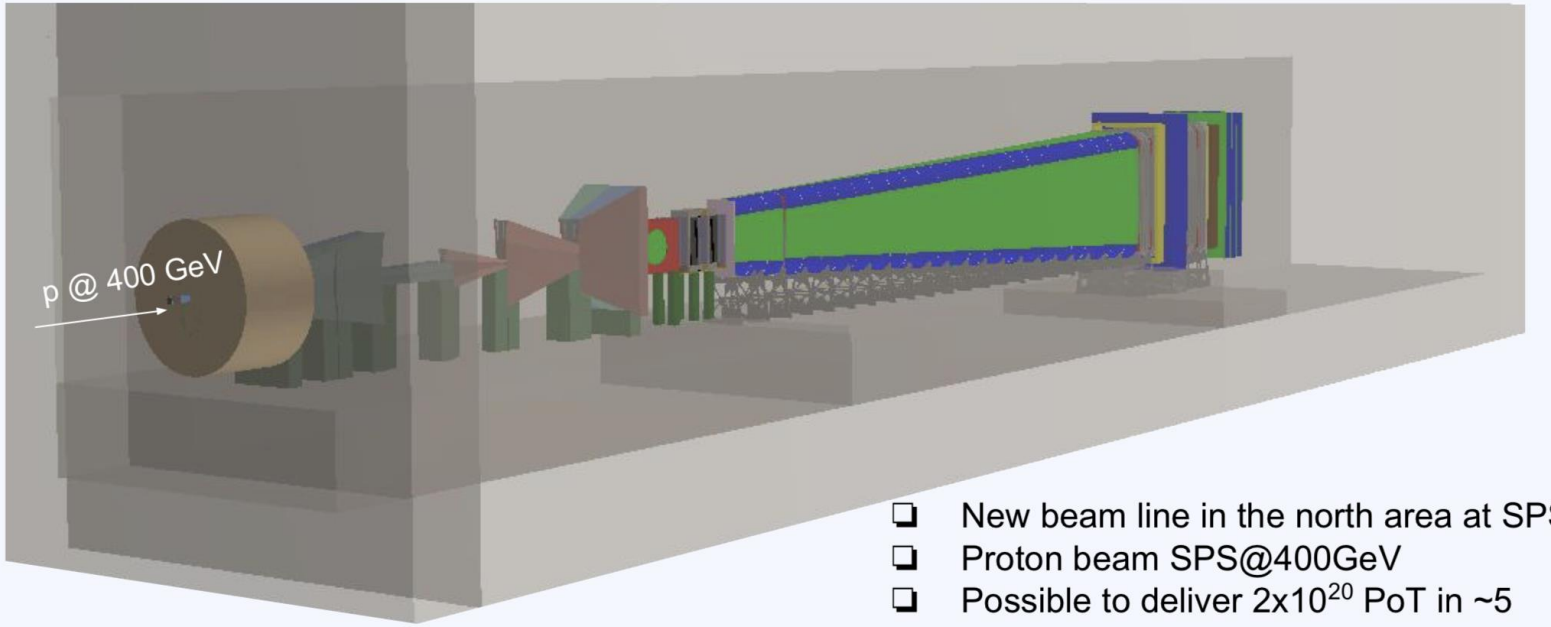
Input from ATLAS, CMS, LHCb, proposed specialized experiments and theory
Complete by fall 2018
(~ 200 pages)

Also meetings with LHC Dark Matter group

SHiP Beam Dump Experiment Proposal

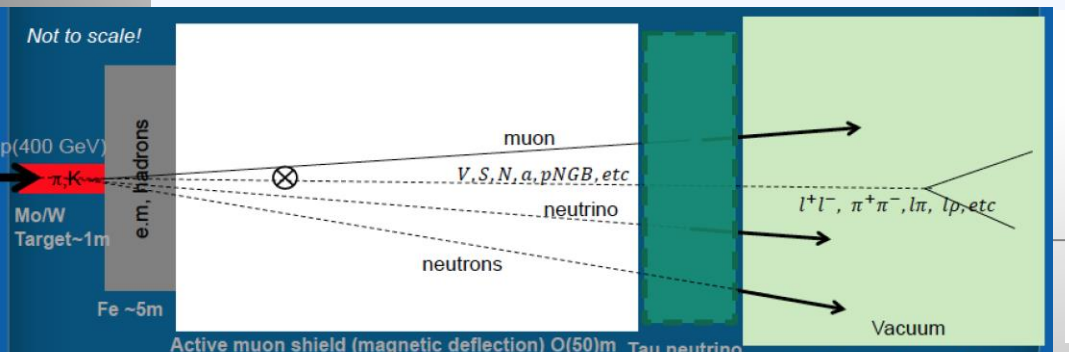
SHiP is a proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to O(10) GeV and weak couplings, down to 10^{-10} .

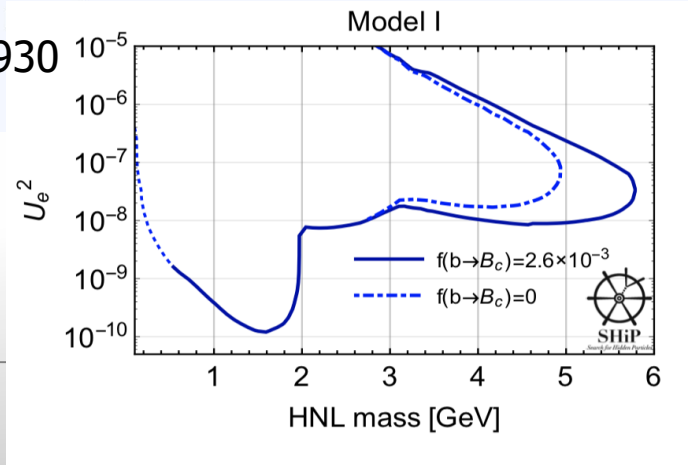
arXiv:1504.04956



- New beam line in the north area at SPS
- Proton beam SPS@400GeV
- Possible to deliver 2×10^{20} PoT in ~5 years

arXiv:1811.00930





CERN High Beam Intensity Initiative

Status and Prospects of PHYSICS BEYOND COLLIDERS at CERN

Study Group mandated by the CERN Management
to prepare the next European HEP strategy update (2019-20)
(coordination: J. Jäckel, M. Lamont, C.V.)

Excerpt from the mandate:

"Explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world."

Time scale: next 2 decades

Physics Beyond Colliders at CERN 1

Many studies on
long lived particles

- Axions & ALPS
- Dark photons & scalars
- Heavy neutral lep[tons
- Millicharges
- Electric dipole models
- …

Summary plots of the reach are being completed for the European Strategy Document (December)

Next workshop (January)
https://indico.cern.ch/event/755856/

NA62, NA64, SHIP, LHC new experiments…

Possible CERN Beam Dump Facility

Foreseen to be sited close to the North Area

Conceptual design well advanced.

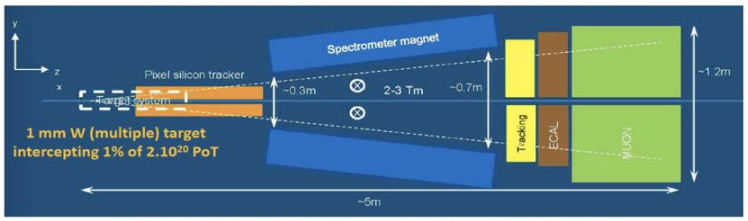
SPS extraction to beamdump target

An opportunity for a new post-CNGS high intensity general facility at CERN

TauFV

Recently revived idea to intercept small BDF beam fraction to look for $\tau \rightarrow 3\mu$ decays

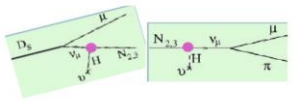
Could set limits on branching ratio better than 10^{-10} level (> BELLE-II reach)



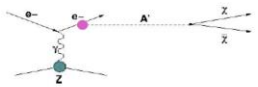
Implementation layout upstream of BDF target under study

A promising option to maximize the physics reach of the Beam Dump Facility

Hidden sector searches

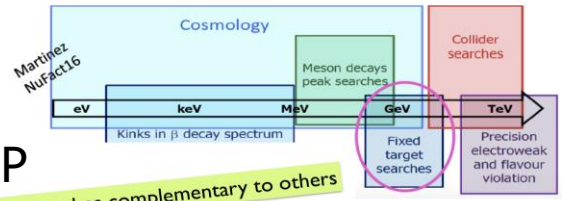


2 methods



Production + decay of new particle: 2 couplings → needs high intensity

Invisible decay of new particle: accommodates lower intensity



SHiP

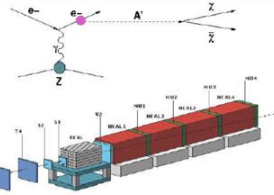
Fixed Target searches complementary to others

Examples of Beyond Collider Studies

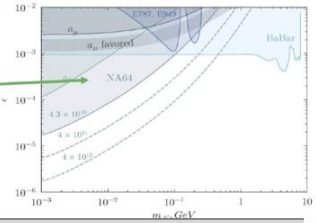
The PBC-book will be out in ~ a week

NA64

Hidden sector search from invisible decays with missing energy



Implemented in 2016 on e test beam

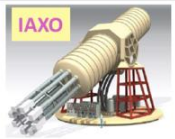


Fast analysis excluding $(g-2)_\mu$ interpretation confirms the potential of the method

AFTER LS2:

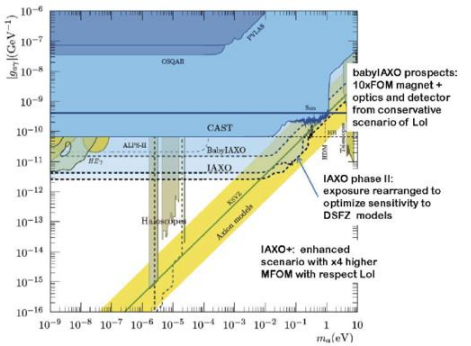
Wish to extend the method to higher e intensity and μ / π / K / p beams

IAXO - next generation Axion helioscope beyond CAST

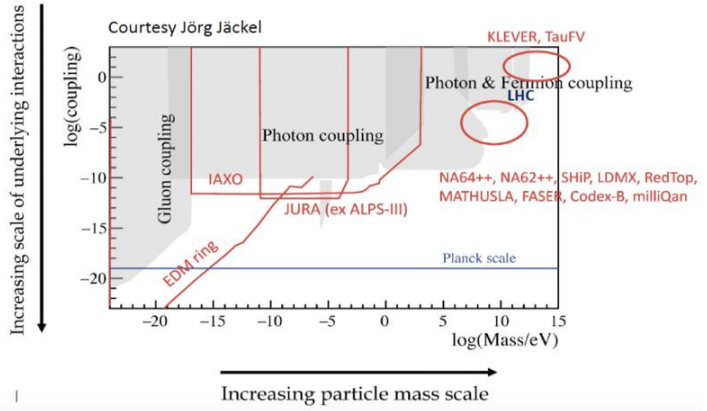


Free bore [m]	0.6
Magnetic length [m]	10
Field in bore [T]	2.5
Stored energy [MJ]	27
Peak field [T]	4.1

10x CAST MFOM

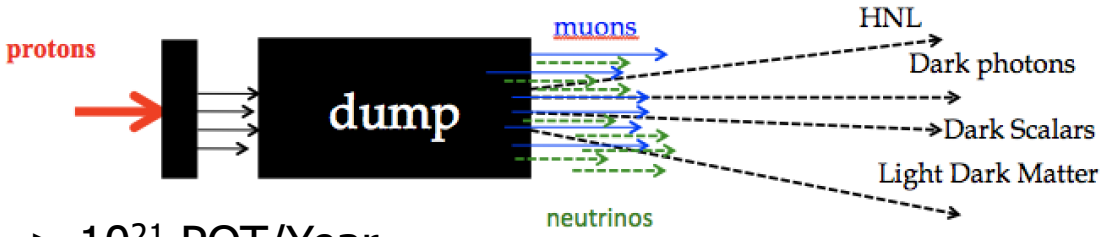


Support from CERN for magnet design within PBC



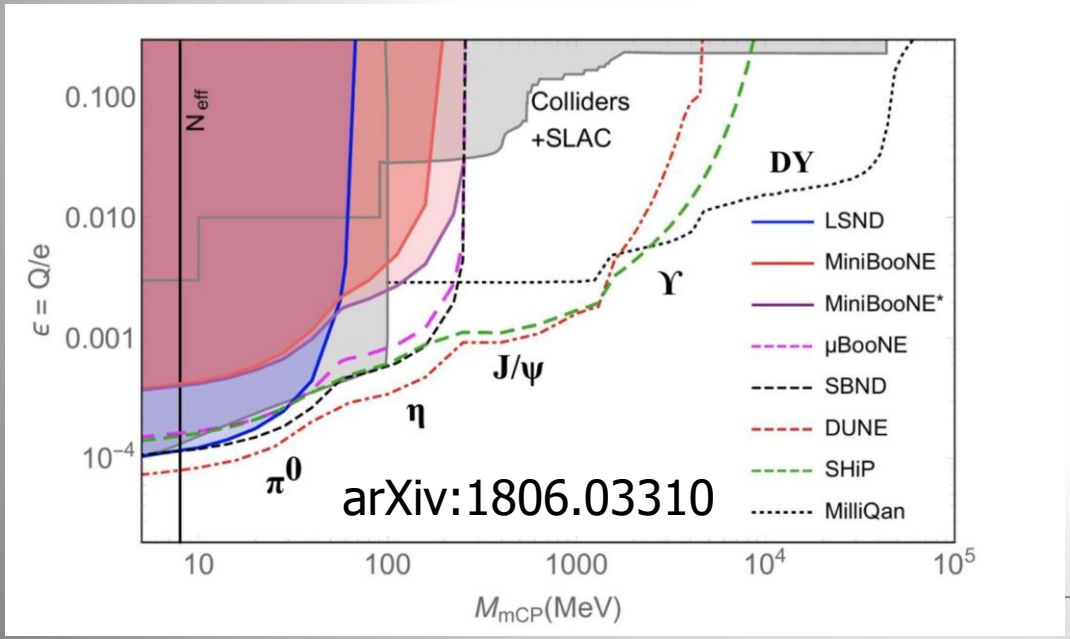
Beam Dump Experiments

High intensity frontier for low mass particles with very weak couplings
->upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams



> 10^{21} POT/Year

Near Detector:
few 100m away
from the dump

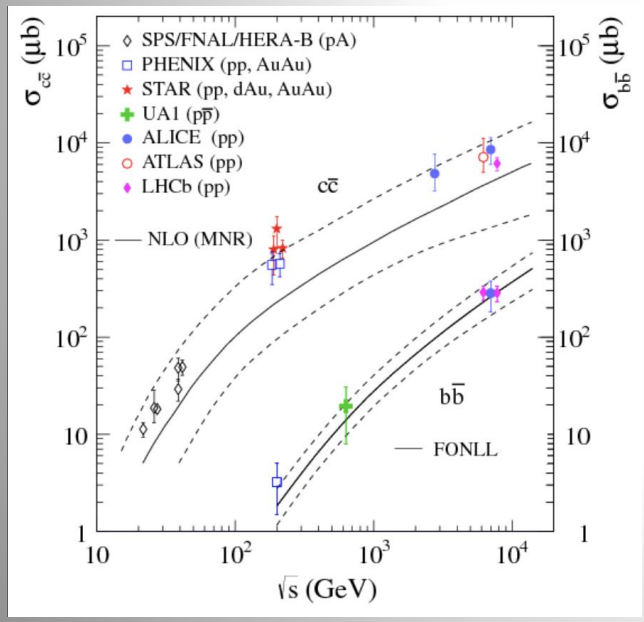


These experiments can
perform searches for low
mass New Physics particles eg
-HNL/sterile neutrinos
-dark photons
-ALPs
-mini/millicharges
…

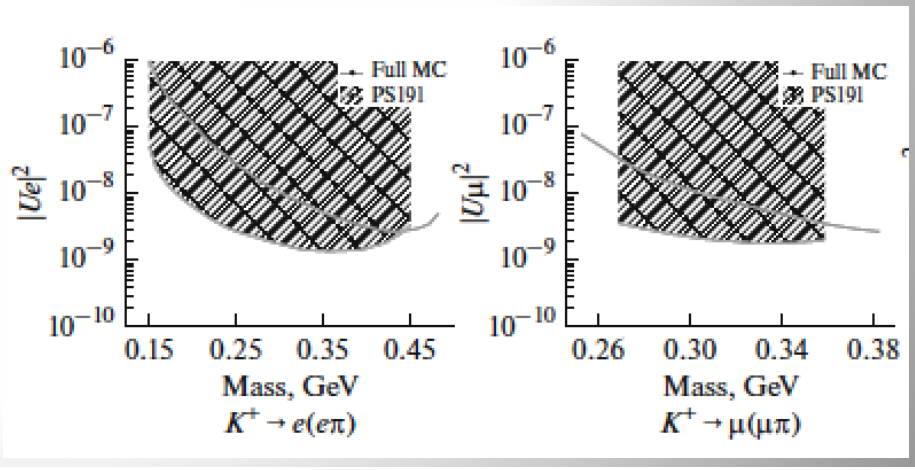
<- Example for millicharges
FerMINI @FNAL?

SHiP <-> Neutrino Beam Dump

- SHiP: 400 GeV protons with 4e19 POT/year
- DUNE: 80/120 GeV protons with 1-2e21 POT/year
- Optimized acceptance for SHiP
- For the NDs the HNL search is not their main program
- Example HNLs via heavy flavor decays: cross sections strongly energy dependent



Comparison of the sensitivity?



Low mass study for T2K for 8e20 POT

Physics of Particles and Nuclei, 2017, Vol. 48, No. 6, pp. 984-

Summary

- Clearly and increased interest in LLP searches at the LHC in CMS, ATLAS, LHCb, MoEDAL. Many analyses done or in are progress. No signal observed yet, but only top of the iceberg covered so far.
- LLP White Paper coming (LHC). Many ideas for new analyses yet to be analysed for the LHC data
- New ideas for additional small experiments at the LHC to increase the coverage: MilliQan, MATHUSLA, CODEX-b, FASER, AL3X. Future beam dump experiments (SHiP). LLPs also focus in the Physics Beyond Collider studies
- Of interest to study in detail the complementarity with LLP searches at Neutrino Near Detectors. Can these be further optimized?

BACKUP

Status of the Various Projects

Lifetime frontier

Simon Knapen FNAL seminar

Supplementary detectors

	Higgs decay	B-meson decay	π,η-decay (dark photon)	Progress	Cost
FASER		✔	✔	Collaboration formed	$
CODEX-b	✔	✔		sub-collaboration formed	$
SeaQuest			✔	experiment exists	$
AL3X	✔	✔	✔	Proof of concept	$$
MATHUSLA	✔	(✔)		Letter of intent	$$
SHiP		✔	✔	Technical design report	$$$

MOEDAL: monopoles, already running

MiliQan: milicharged particles, phase 1 detector in place

Similar timelines for MATHUSLA, MilliQan CODEX-b, FASER

Mass-cτ Coverage (2017) HV Pions